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Abstract

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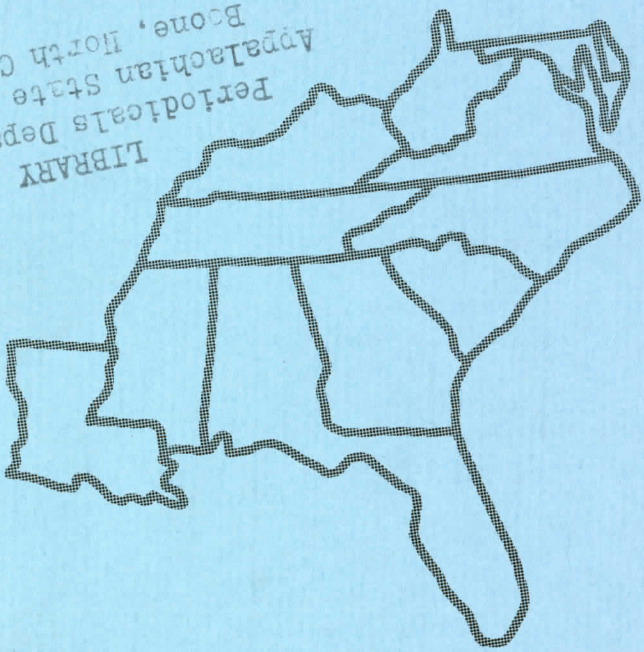

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SOUTHEASTERN GEOLOGY

Table of Contents

Vol. 16, No. 1

1974

INSELBERGS ON THE PIEDMONT OF VIRGINIA, NORTH CAROLINA, AND SOUTH CAROLINA: TYPES AND CHARACTERISTICS

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ABSTRACT

The purpose of this study is to examine the morphologic characteristics of the Piedmont inselbergs and to determine the nature of the processes that give rise to these forms. The landform elements studied include the inselberg side-slope profile, the piedmont slope adjacent to it, the piedmont angle between the inselberg side-slope and the piedmont surface, and the thickness and characteristics of the waste cover.

Inselbergs on the Piedmont are grouped into four types based on their association with or isolation from other landforms. The necessary prerequisites for the development of the inselberg landscape are sufficient relief and crustal stability to allow lateral replacement of the mountain escarpment. Slopes below the critical relief or with gentle gradients tend to downwaste. The underlying rock type is important in determining the slope gradients, piedmont angle, and regolith characteristics. The major processes shaping the Piedmont inselbergs are chemical weathering, solution, throughflow, overland flow, and gullying.

INTRODUCTION

Inselbergs, isolated mountains that protrude from nearly flat plains, have been described in many areas of the world. These hills are the result of degradational processes that have reduced a previously more extensive mountain mass to erosional remnants. The resultant landform assemblage is a residual hill, surrounded by an erosion surface that slopes away from the base of the hill and forms some manner of junction at the base of the hill side-slope. The major attempts to explain the formation of inselbergs have embraced a climatogenetic approach, associating them with arid and tropical savanna environments that have characteristics similar to the inselbergs in these other areas. An example of inselbergs in a humid temperate climate is found on the Piedmont region in the eastern United States.

The purpose of this study is to examine the morphologic character of the inselbergs on the Piedmont of Virginia, North Carolina, and South Carolina, and to determine the processes that give rise to these forms in a humid temperate environment. Among the landform elements examined were the inselberg slope profile, the erosion surface immediately adjacent to it, the break in slope between the residual hill and the erosion surface, and the characteristics of the waste cover. In addition, the distribution of inselbergs is examined and their position is described in relation to other landform features (e. g., mountain scarps, ridges), allowing the inselbergs to be loosely grouped into landform associations.

Acknowledgments

The writer is grateful to Frank Ahnert, University of Maryland, for his comments and criticisms, which can only have improved this work. The assistance of graduate students, D. McDermott, R. Oudemans, and J. Duncan at the University of Maryland in carrying out field work is also greatly appreciated.

FIELD AND LABORATORY PROCEDURES

All inselbergs were examined on aerial photographs, topographic, soils, and geologic maps to determine the size parameters, the rock type underlying the inselberg and adjacent piedmont, and the structural trends.

Inselberg slope profiles were surveyed with an Abney hand level and tape to the nearest half degree; for analysis and comparison, the profiles were marked out in equal intervals of 100 feet. Measurements of the waste cover thickness were made at each interval along the slope profile with a portable seismic timer (Dyna Metric Model R-117B). Waste cover thickness was calculated from the time-distance data according to the method outlined in the operating manual.

To determine the characteristics of the waste cover, samples were taken at the measured intervals along the profile on selected slopes from the upper four inches and, intermittently, from depths of 12 and 18 inches. All the samples were mechanically analyzed by wet sieving, and the silt and clay fractions were determined by the hydrometer method. The type of feldspar was determined in the 2-to-4mm fraction of the waste cover samples, using the staining method described by Reeder and McAllister (1957). After staining, the percentages of feldspar, quartz, and mica were ascertained by counting 300 randomly selected grains under a low power microscope. If a fragment was composed of more than one mineral, an estimate was made for each mineral.

PREVIOUS WORK ON THE ORIGIN OF INSELBERGS

Over the past years, a number of hypotheses have been offered on the genesis of inselbergs. Many of these hypotheses have emphasized the role of climate, particularly in arid and tropical savanna environments. Inselbergs were first described in, and considered indigenous to, tropical savanna areas (Bornhardt, 1900). In tropical areas, especially the wet-dry savanna climate, inselbergs have been considered to be residual rock masses, developed under a thick, chemically weathered regolith, characteristic of the humid tropics and subsequently exhumed during a renewed cycle of erosion (Budel, 1957; Thomas, 1965). The resistant rock masses are attributed to the spatial variation in the density of joints in the underlying bedrock. This difference in joint density causes those rocks that are less shattered to be less susceptible to chemical and fluvial processes. The weaker, jointed rock mass is more easily weathered and eroded, leaving the inselberg as a residual. Investigators have indicated that inselbergs are also found in large numbers in humid tropical regions (Louis, 1959; Barbier, 1957).

Within arid environments the inselberg is considered as a residual feature resulting from the retreat of a mountain front. Inselbergs appear to form as the detached ends of spurs that extend from the mountain front. They remain connected to the mountain front by a pediment surface and meet the pediment in an abrupt angle. There are two generally accepted explanations to account for the mountain-front retreat and the resulting arid inselberg landscape. One hypothesis attributes the landscape forms to the lateral planation by steep-gradient, ephemeral streams (Blackwelder, 1931); the other contends that such features are caused by weathering processes and erosion by sheet and rill wash (Lawson, 1915). Some writers have combined certain features of these two concepts (Bryan, 1925).

A number of writers have attempted to discredit the climatogenetic explanation for inselberg development and have emphasized instead the role of structural control (King, 1962; Twidale, 1971). King (1966) feels that deep weathering is not a necessary prerequisite for the development of inselbergs, but that stream incision along joints and the subsequent parallel retreat of marginal slopes will give rise to inselbergs. In summarizing the important factors for inselberg formation, King (1962, p. 149) includes rock type, scarp retreat, and sufficient available relief. Twidale (1971, p. 50-55) considers differences in joint density followed by compartment-type weathering as important to inselberg formation. Penck (1924, p. 194) has emphasized that inselberg formation is favored by a stable base level.

In some areas the inselbergs have been attributed to past climates. Demek (1964) concludes that inselbergs in the Bohemian Highlands were formed under more humid conditions than at present. Perret (1953) suggests a similar origin for inselbergs in the Ahaggar.

Several authors have used particular types of residual hills as indicators of climatic change (Bakker and Levelt, 1964; Schwarzbach, 1963, p. 67).

The concept of landscape evolution in the humid temperate climate, including the Piedmont area, has been dominated by the ideas of W. M. Davis, according to whom (Davis, 1922, 1932), a mountain mass is reduced by valley widening. Davis contended that as the valleys are widened, the bordering slopes tend to attain gentler gradients during their retreat. The forested valley slopes were seen to be eroded by wash and soil creep. The landscape is ultimately reduced to a peneplain, a surface of little or no relief with broad convex interfluves. Near the final stage of reduction, inselbergs (monadnocks, according to Davis), rising above the erosion surface, result from their superior resistance or their remoteness from major drainage lines. The latter type of inselberg tends to be composed of the same rock type as the adjacent piedmont surface. He described the monadnocks as having gentle convex slopes that merge without any sharp demarcation into the surrounding piedmont surface.

An alternative hypothesis for landscape development in humid temperate areas was proposed by Hack (1960). He assumed that all slopes are mutually adjusted so that they are downwasting at the same rate. The topography is considered to be in a steady state and will remain unchanged as long as rates of erosion and uplift remain constant.

Neither of these concepts adequately explains the inselberg landforms found on the Piedmont. It is suggested here that some form of slope replacement must also be considered to explain the Piedmont inselbergs and their associated landforms.

DEFINITION OF TERMS

In this study the term "inselberg" is used in a descriptive sense to designate an isolated hill that emerges from a surrounding plain. The definition is limited to erosional remnants that are the result of subaerial processes, and it includes such features as mesas, buttes, or tors. If a more exact definition is desired, a modifier or series of modifiers can be used (e. g., granitic, mesa-type). The term "bornhardt," sometimes used synonymously with inselberg, is defined as a special type of inselberg, composed of massive rock and characterized by a domal shape (Willis, 1936). The word "monadnock" is not used because of its genetic implications in the writings of W. M. Davis, Birot (1952) has used the term "inselberg" to describe the isolated mountains on the Piedmont that Davis envisaged as monadnocks.

The inselberg, for the purpose of this study, was limited to erosional remnants that had a length to width ratio less than 5:1. This was done to eliminate elongate ridges that may owe their form to erosion processes, but are not the characteristic "island mountain" generally associated with the concept of inselbergs.

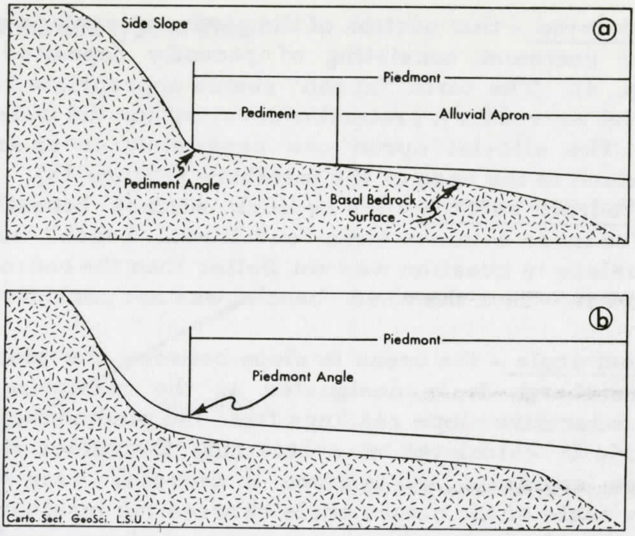


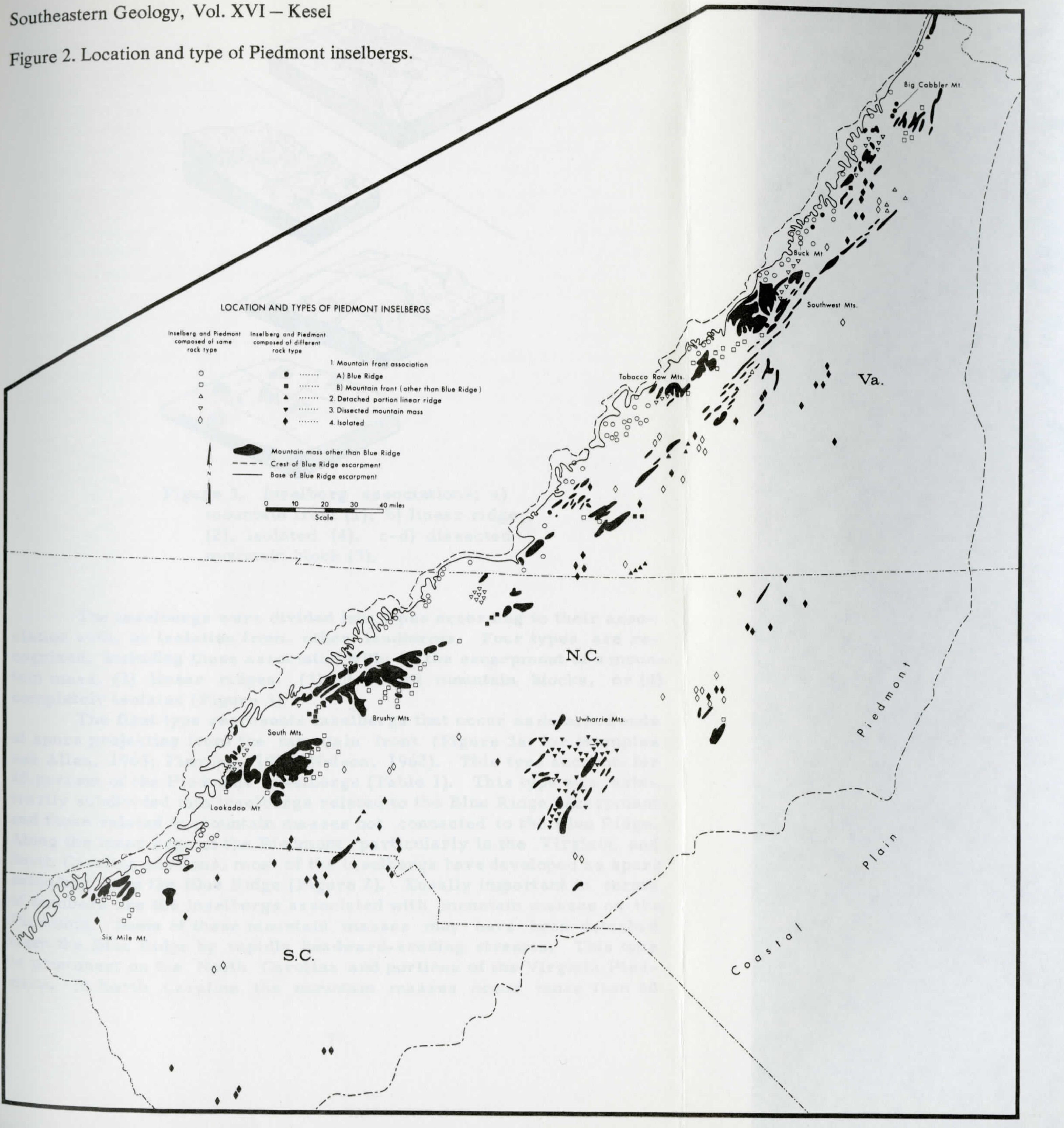
Figure 1. Landforms associated with the inselberg landscape; a) exposed pediment surface, b) piedmont surface with alluvial or soil cover.

The other landforms associated with the inselberg landscape are defined below (Figure 1). To avoid confusion, these terms are used in a non-genetic sense.

Piedmont - the surface that extends out from the base of the inselberg, regardless of the nature of the surface, whether it be soil covered or bedrock. The upper boundary of the surface with the inselberg is the piedmont angle (see discussion below). It has been suggested that the maximum gradient of this surface on its upper edge is 12 degrees (Rahn, 1966; Cooke, 1970). Because this estimate was supported by the location of the piedmont angle in the field (Kesel, 1972), the upper limit of the piedmont surface was defined as not exceeding a gradient of 12 degrees. Such a limit is necessary especially in cases where no sharp break is apparent at the base of the inselberg.

Pediment - the exposed bedrock portion of the piedmont adjacent to the inselberg (Figure 1a). The surface of the pediment may be covered by a thin veneer of alluvial sediments that is in the process of being transported downslope. Along its outer edge, the pediment disappears beneath the alluvial sediments. The outer edge of the pediment is defined where the bedrock surface could no longer be observed in the bottoms of gully channels. This outer limit was chosen because it is the point past which gully bottoms are no longer in contact with the bedrock surface, and active scouring of this surface may no longer take place. The upper limit of the pediment is its junction with the inselberg.

Figure 2. Location and type of Piedmont inselbergs.



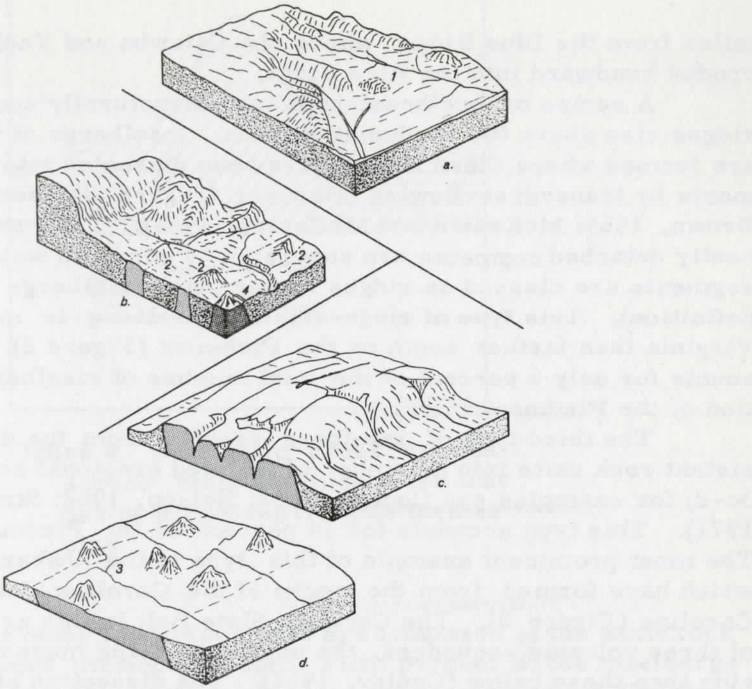


Figure 3. Inselberg associations; a) mountain front (1), b) linear ridge (2), isolated (4), c-d) dissected mountain block (3).

The inselbergs were divided into types according to their association with, or isolation from, other landforms. Four types are recognized, including those associated with: (1) the escarpment of a mountain mass, (2) linear ridges, (3) dissected mountain blocks, or (4) completely isolated (Figure 3).

The first type represents inselbergs that occur as detached ends of spurs projecting from the mountain front (Figure 3a; for examples see Allen, 1963; Fleming, 1958; Nelson, 1962). This type accounts for 45 percent of the Piedmont inselbergs (Table 1). This type was arbitrarily subdivided into inselbergs related to the Blue Ridge escarpment and those related to mountain masses not connected to the Blue Ridge. Along the inner edge of the Piedmont, particularly in the Virginia and South Carolina portions, most of the inselbergs have developed as spurs extending from the Blue Ridge (Figure 2). Equally important in terms of numbers are the inselbergs associated with mountain masses on the Piedmont. Some of these mountain masses may have been detached from the Blue Ridge by rapidly headward-eroding streams. This type is prominent on the North Carolina and portions of the Virginia Piedmont. In North Carolina the mountain masses occur more than 40 miles from the Blue Ridge, where the Catawba and Yadkin rivers have eroded headward into the Blue Ridge.

A series of northeast-trending, structurally controlled, linear ridges rise above the Piedmont surface. Inselbergs of the second type are formed where these ridges have been dissected into smaller segments by transverse-flowing streams (Figure 3b; for examples see Brown, 1969; McKenzie and McCauley, 1968). The younger, more recently detached segments are separated by wind and water gaps. Some segments are classed as ridges rather than inselbergs (see inselberg definition). This type of ridge-related inselberg is more common in Virginia than farther south on the Piedmont (Figure 2). Overall it accounts for only 6 percent of the total number of inselbergs on this portion of the Piedmont.

The third type of inselberg results from the dissection of resistant rock units into a number of isolated erosional remnants (Figure 3c-d; for examples see Conley, 1962; Nelson, 1962; Stromquist, et al., 1971). This type accounts for 24 percent of the Piedmont inselbergs. The most prominent example of this type is the Uwharrie Mountains, which have formed from the rocks of the Carolina Slate Belt of North Carolina (Figure 2). The Carolina Slate Belt in this area is composed of three volcanic sequences, the upper one being more resistant to erosion than those below (Conley, 1962). The dissection of these rocks by the Yadkin-Peedee River has formed a number of inselbergs that are capped by a resistant volcanic layer.

The fourth type includes inselbergs that are completely isolated and apparently are not related to any of the other associations (Figure 3b; for examples see Butler and Dunn, 1968; Dunn and Weigand, 1969; Allen and Wilson, 1968). These inselbergs are generally located nearer the outer edge of the Piedmont than the other types and account for 25 percent of the total. In some cases the isolated type may have been formed as one of the other types, with the evidence for this association obscured by subsequent erosion. The classification of this type was the most difficult, and several arbitrary criteria were chosen to separate it from the other types. First, the inselberg had to lie at least 5 miles from either a mountain front or a linear ridge. Second, it could not be within 5 miles of another inselberg, if the two inselbergs were located on the same continuous rock unit. If this latter criterion was not met, the remnant could belong to either type two or three.

The rock type that underlies the inselbergs and the adjacent piedmont slopes was determined from available geologic maps and soil surveys. Maps at scales greater than 1:200,000 were considered to be accurate enough to determine these differences in rock type, although the accuracy falls off rapidly at scales smaller than 1:62,500. Maps at scales smaller than 1:200,000 were used only if no other source was available. Although there are variations in the figures derived from the different map scales, similar trends in the data are apparent.

Eighty-seven percent of the inselbergs associated with either

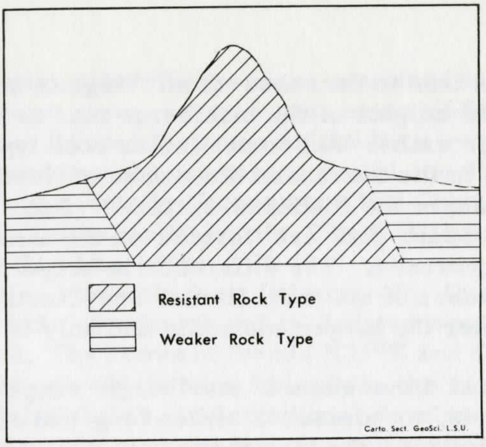


Figure 4. Schematic cross section across resistant rock mass that has been reduced from its former size.

the Blue Ridge or other mountain fronts are composed of the same rock type as the adjacent piedmont slope. Fifty percent of the inselbergs formed from dissected mountain masses are composed of the same rock type as the piedmont slope, while only 25 percent of the inselbergs that are either related to linear ridges or are isolated types fit into this category. In some cases the inselberg results from local structural conditions such as described later for Six Mile Mountain or from differences in joint density (Fleming, 1958). In many cases the inselberg and piedmont slope that are underlain by the same rock type appear to have been formed as a result of the degradation of a larger resistant rock mass (Figure 4). Some of the linear ridges also exhibit this degraded type of cross section. Several examples can be found on the large-scale maps in studies by Brown (1958) and Nelson (1962). An examination of the distribution of Piedmont inselbergs indicates that resistant type remnants (e. g., lithology, joints) are located fartherest from the mountain fronts (Figure 2). This may indicate that inselbergs formed from the same rock type as the adjacent piedmont surface (e. g., type 1, Figure 3) have a much shorter duration in the landscape than the more resistant types.

The elevation and relief of the inselbergs show a random spatial distribution. The summit elevations do not become progressively lower toward the southeast away from the Blue Ridge escarpment. Some peaks are nearly equal to or surpass the Blue Ridge in elevation. There is also little correspondence between the relief of the inselbergs and their distance from the Blue Ridge.

The average height of the inselbergs on the Piedmont is 265 feet, and this ranges from 60 to 1,321 feet. The average height and the number of remnants tend to decrease from Virginia southward toward South Carolina. The heights of the inselbergs tend to be related to the thickness of the beds rather than to particular rock types. For example, two inselbergs in the Suaratown Mountains of North Carolina stand 227 and 1,321 feet above the Piedmont surface. Both inselbergs are less than two miles apart and are formed on the same bed of steeply dipping, resistant quartzite. The difference in height can be attributed to variation in thickness of the bed (Butler and Dunn, 1968). The bed is 200 feet thick under the larger mountain and only 60 feet thick under the smaller one.

The horizontal dimensions of inselbergs range from 880 feet long and 715 feet wide, to almost 3 miles long and a little more than 2 miles wide. In plan view the inselbergs have a variety of shapes. An elliptical plan is most common; other shapes include elongate mountains, with one or more spurs giving a V or W-shaped outline, and those with a circular base. The latter type is the least common. The former type reflects the control by joints.

The orientation of the long axis of the Piedmont inselbergs is predominantly northeast-southwest. There is a tendency for this orientation to change to a more easterly direction southward from the Virginia to the South Carolina Piedmont. The inselbergs of Virginia and South Carolina also exhibit a secondary trend of northwest-southeast: this secondary trend is not as prominent in the North Carolina Piedmont. The general northeastward trend of the inselbergs is controlled by the lineation and the strike of the bedding of the underlying bedrock. The secondary, northwest trend is characteristic of many of the inselbergs associated with the Blue Ridge and is presumably related to the southeast-flowing streams that flow down the escarpment. These streams have dissected the escarpment into a series of spurs and intervening coves or valleys. These spur ends are possible loci of inselberg production. The numerous angular changes in direction of these spurs indicate that the dissection is in large part guided by joint directions.

The effect that joints have on the orientation of inselbergs is not easily measured because of the deep regolith cover. An insufficient number of joint trends was measured to be able to generalize for the entire Piedmont. However, measurements made on individual inselbergs, especially those composed of massive rocks, indicate that joints play a role in determining the outline of these remnants.

ANALYSIS OF INSELBERG LANDFORM

ELEMENTS AND WASTE COVER

Inselbergs Examined

In order to assess the characteristics of the landform elements and the waste cover, 4 inselbergs were examined in detail, and supplemental observations were carried out on an additional 25 remnants. The sampling was limited because of the time required to survey and sample the long and heavily vegetated, humid inselberg slopes. Inselbergs included in the detailed survey are Big Cobbler and Buck mountains in Virginia, Lookadoo Mountain, North Carolina, and Six Mile Mountain, South Carolina (Figure 2).

Big Cobbler Mountain (see Orleans, Va. Quad., U. S. G. S.) rises 838 feet above the Piedmont and is located 6 miles east of the Blue Ridge escarpment. The remnant trends N15°E and is elongate along the strike of the bedding, which dips steeply to the southeast. The rocks exhibit several joint planes, including one developed perpendicular to the bedding plane. The remnant and the adjacent piedmont surface are underlain by the Marshall Formation, which consists of a gray, coarse- to fine-grained, hornblende gneiss (Va. Div. Min. Res.). Examination of hand specimens indicates that fine-grained rocks outcrop along the crest of the inselberg, and coarser grained rocks are found along its flanks and on the piedmont. The coarse-grained rock tends to weather more rapidly than the fine-grained (Kock, 1968, p. 13) forming an inselberg that is more resistant than the adjacent piedmont surface.

Buck Mountain (see Free Union, Va., Quad., U. S. G. S.) is 1.75 miles from the base of the Blue Ridge escarpment. It rises almost 700 feet above the surrounding surface. The trend of the inselberg is N 36° W and is transverse to the strike of the rocks. The bedding planes in these rocks strike to the northeast and dip steeply to the southeast. Joints are most prominently developed in a northwest-southeast direction. Both the inselberg and the adjacent piedmont are underlain by the Lovingston Formation, fine-to medium-grained gneiss (Allen, 1963).

Lookadoo Mountain (see Sunshine, N. C. Quad., U. S. G. S.) is the detached end of a small spur that extends from the southern end of the South Mountains and is separated from the spur by a col. or low pass. The South Mountains have been separated from the Blue Ridge by the headward erosion of the Broad and the Catawba rivers. The inselberg stands 360 feet above the piedmont surface. It has a trend to the northeast that, like Buck Mountain, is transverse to the strike of the bedding. Joints are well developed in two directions, to the northeast and to the northwest. The area is underlain by a Precambrian schist (Le Grande and Mundorff, 1952), but any differences between the inselberg and the adjacent piedmont could not be determined because of the limited number of bedrock outcrops.

Six Mile Mountain (see Six Mile Mt., S. C. Quad., U. S. G. S.) is approximately 8 miles south and 15 miles east of the Blue Ridge and has a relief of 401 feet. The trend of the remnant is northwest-southeast and is transverse to the strike of the bedding in the rocks. The inselberg crest and the surrounding piedmont are underlain by a Paleozoic muscovite mica schist, while a biotite gneiss of similar age

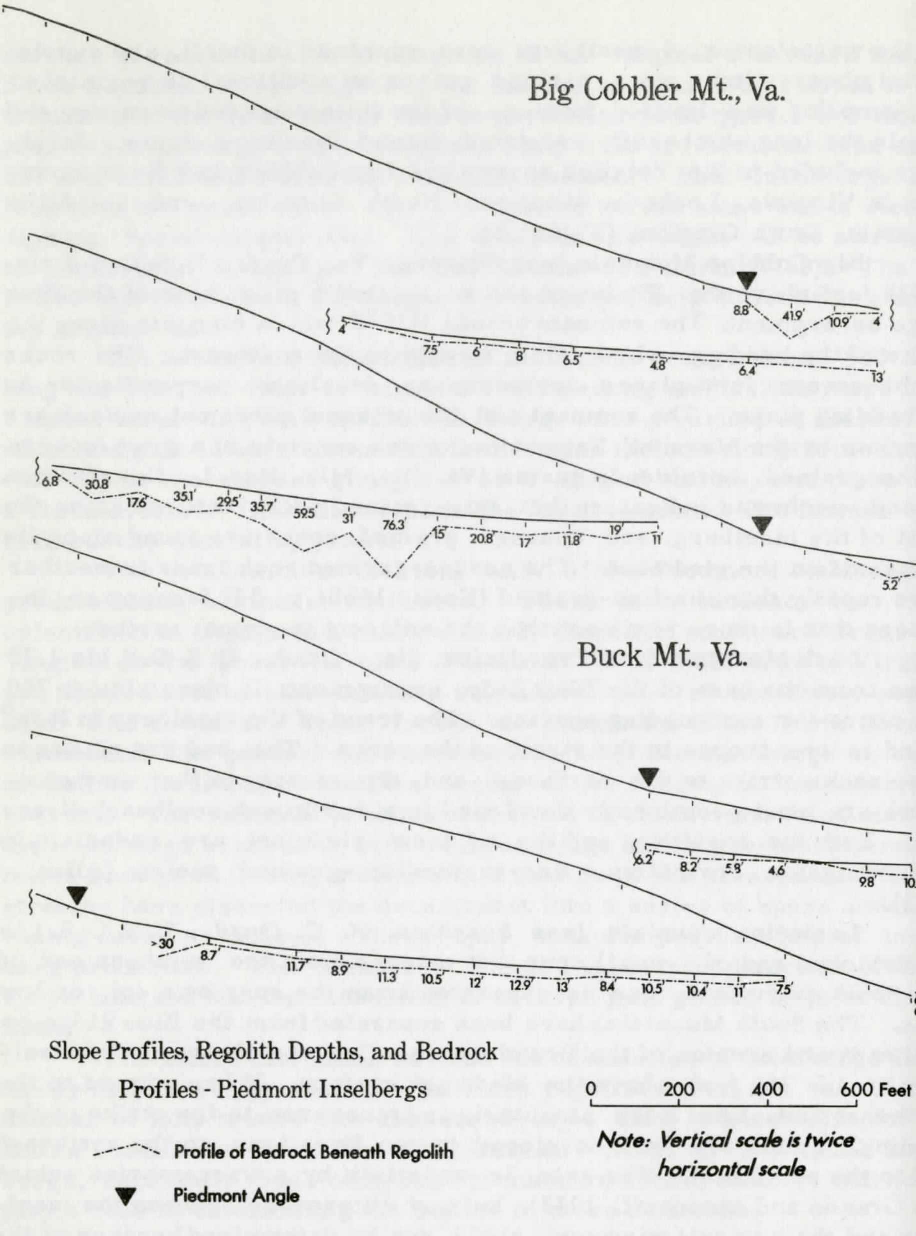
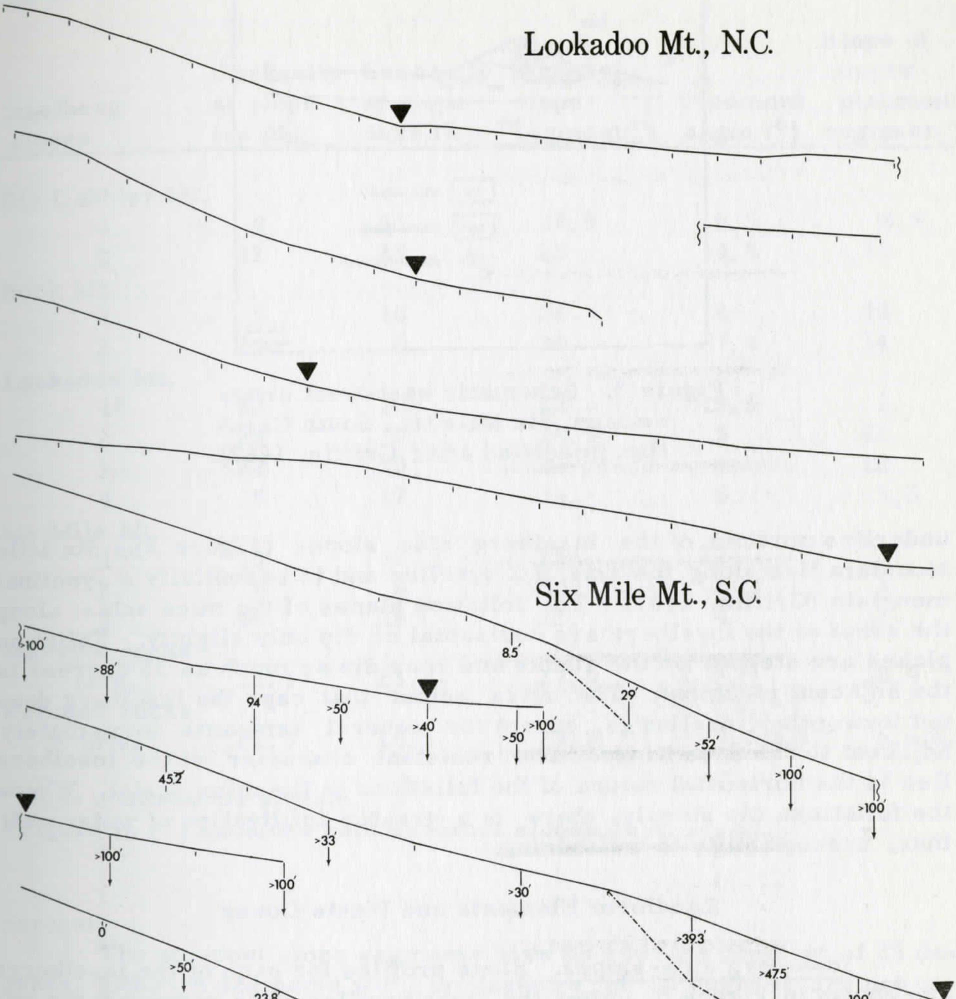


Figure 6. Slope profiles, regolith depths, and bedrock profiles - Piedmont inselbergs.



Lookadoo Mt., N.C.
Six Mile Mt., S.C.
>100'
>88'
94'
>50'
>40'
8.5'
29'
>50'
>100'
>52'
45.2'
>100'
>100'
>33'
>100'
>100'
>30'
>39.3'
0'
>50'
>47.5'
23.8
100'
>35.5
53.3'
>67'
>67'
>100'
5.6'
>100'
>100'
>100'
>100'
>67'
>100'
>100'
46.5'
>100'

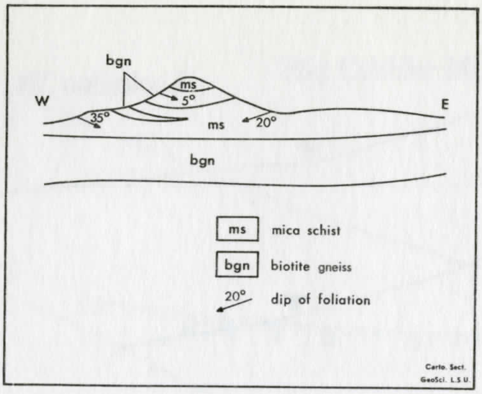


Figure 5. Schematic east-west cross section, Six Mile Mt., South Carolina (modified after Griffin, 1967).

underlies portions of the inselberg side slopes (Figure 5). Six Mile Mountain lies along the axis of a syncline and is essentially a synclinal mountain (Griffin, 1967). The foliation planes of the mica schist along the crest of the inselberg are horizontal or dip only slightly. Foliation planes are steeper on the flanks and may dip as much as 35 degrees in the adjacent piedmont. The mica schist that caps the inselberg does not form other inselbergs, except for several remnants immediately adjacent to the Blue Ridge. The resistant character of the inselberg lies in the horizontal nature of the foliations in the mica schist. Where the foliations dip steeply, there is a greater infiltration of water and, thus, susceptibility to weathering.

Landform Elements and Waste Cover

Inselberg side-slopes. Slope profiles for each of the inselbergs are shown in Figure 6. After the slope profiles were surveyed, the approximate percentage of convexity at the top and concavity at the base of the side-slopes was determined using the method described by Ahnert (1970b). The inselberg slopes are composed of a number of concave and convex segments throughout their profiles. The convex portion at the top accounts for 10.5 to 29.5 percent of the profile (Table 1). Profiles on foliated rocks tend to have a greater degree of convexity than those on massive rocks. The concave portion at the base of the slope ranges from 10 to 32.5 percent of the profile. On massive rocks the concave portion is almost 22 percent, while on foliated rocks it is 29.5

Table 1. Characteristics of Piedmont Inselberg Slope Profiles.

Inselberg slopes	Convexity at slope top (%)	Concavity at slope base (%)	Steepest slope segment(°)	Piedmont angle (°)	Slope of upper piedmont segment(°)
Big Cobbler Mt.					
1	9	32	28.5	5.5	8.5
2	12	23	25	14.5	11
Buck Mt.					
1	5	10	28	8	10
2	19	0	30	7.5	14
Lookadoo Mt.					
1[a]	22	16	22	15.5	1
2	24	0	29.5	5	12
3	22	50	22	4	12
4	8	17	14	5	3.5
Six Mile Mt.					
1[a]	13	47	25	27	3
2	0	0	30	6	3
3	46	18	22	4	12
Massive rocks (ave.)	11.3	21.7	27.9	8.9	10.9
Foliated rocks (ave.)	22.5	29.5	23.5	9.5(4.8)[b]	6.6(8.5)[b]

[a]Slope undercut by stream.
[b]Figure in ( ) excludes both undercut slopes.

percent.

The steepest slope segments have an average gradient of 25 degrees, although segments with inclinations of 30 degrees are not uncommon (Table 1). Portions of slope segments on massive rocks have stepped profiles that are coincident with joint planes. Along these joints, slopes can become almost vertical. According to Table 1, the massive rocks have slightly steeper slopes than the foliated rocks.

Piedmont angle and slope. The piedmont angle at the base of the Piedmont inselbergs is less conspicuous than it is in the arid and tropical savanna areas (Kesel, 1973). The average piedmont angle at the base of the inselbergs is slightly more than 9 degrees, but varies from 4 to 27 degrees (Table 1). The two piedmont angles with the greatest break in slope (Lookadoo Mountain - 1; Six Mile Mountain - 1) appear to be the result of ephemeral-type streams that have eroded headward and over-steepened the side-slope above. If these two values are excluded from the calculation, the average piedmont angle is less than 7 degrees. Rock type appears to have some influence on the variation of the piedmont angle. On the massive rocks, the average angle is almost 9 degrees, compared to approximately 5 degrees on foliated rocks.

The piedmont surface that extends out from the humid inselbergs has a straight to slightly concave longitudinal profile (Figure 6). The slope segment immediately downslope from the piedmont angle gives the general magnitude of the piedmont slope along its upper edge. The average inclination of this segment is about 9 degrees. It is slightly steeper on the massive rocks than it is on the foliated rocks, although this difference may not be too significant (Table 1).

The transverse profile across the piedmont surface has an undulatory character. The surface is crossed by ephemeral channels, which are separated by interfluves that are convex upward. The channels rise in coves or hollows on the inselberg side-slopes. On the flanks of the inselbergs, the channels have V-shaped cross sections with steep sides and can be as much as 40 or 50 feet deep. Where these channels cross the adjacent piedmont surface, they are less steep sided and may be only 10 or 15 feet deep.

Waste cover thickness. On the highly foliated rock of Six Mile Mountain, the regolith cover on the side-slopes ranges from zone with no appreciable thickness to depths greater than 100 feet (Figure 6). One area of relatively thin waste cover was found on the northeast flank of the inselberg. On this slope a stream has eroded headward because of spring sapping along its upper extremity. This action has resulted in a steepening of the slope and removal of the debris cover from the slope segments immediately upslope from the stream. Seismic measurements on Lookadoo Mountain indicate a similar thickness of waste cover.

In comparison, the slopes of Big Cobbler and Buck mountains, composed of massive rocks, have numerous bedrock outcrops and are covered by boulders many feet in diameter. The regolith on these slopes is limited to isolated pockets that, in some cases, can be 20 or 30 feet across. Because of the lack of a continuous waste cover, seismic profiles were not taken on these slopes.

The thickness of the regolith cover on the surrounding piedmont slopes also appears to be greatly influenced by the underlying bedrock. The regolith cover on piedmont slopes developed on foliated rocks is generally deeper than that on the adjacent inselberg slopes. In more than half the sites on foliated rocks where seismic observations were made, the thickness of the cover was greater than 100 feet (Figure 6). In several cases the regolith thickness on both inselberg and piedmont slopes associated with foliated rocks varied as much as 50 feet over a distance of 100 feet. The regolith cover on the piedmont slopes surrounding inselbergs composed of massive rocks is thinner and more uniform in thickness than that of highly foliated rocks (Figure 6). Rock outcrops on these piedmont surfaces are not uncommon. On most of the piedmont slopes on massive rocks, there is little increase in the regolith thickness downslope from the inselberg.

The piedmont surface surrounding Big Cobbler Mountain generally fits into this category. The cover on the western piedmont is, for the most part, less than 10 feet thick and maintains a fairly uniform thickness along the longitudinal profile surveyed (Figure 6). However, the bedrock profile beneath the regolith on the eastern piedmont exhibits several large depressions that increase in size downslope from the base of the inselberg. The difference in the waste cover thickness between the eastern and western piedmont slopes may be explained by the differences in the lithology and/or structure of the underlying bedrock. The variation in the size of the bedrock depression and the corresponding thickness of the overlying waste cover could be the result of differences in joint density.

The contact between the waste cover and the bedrock ranges from a sharp break to a zone that passes from solid rock upward through progressively weathered material. The latter type is by far the most common, although the former is found on the piedmont slopes adjacent to Big Cobbler and Buck mountains.

There is a strong similarity between the profile of the piedmont surface and the ephemeral channels that act as the local base level for the interfluve areas on the surface. Both exhibit longitudinal profiles that are concave upward. On massive rocks the bedrock surface beneath the regolith cover of the piedmont slope also has a concave profile. Seismic measurements taken across gullies on Big Cobbler and Buck mountains indicate that the transverse profiles on this bedrock surface undulate as does the piedmont surface. The regolith cover decreases in thickness from the interfluve areas toward the adjacent gullies.

These data suggest the piedmont surface is in equilibrium and erosion energy remains the same along the longitudinal profile. The result is a surface that is downwasting at a uniform rate similar to that considered by Hack (1960).

<u>Waste-cover characteristics</u>. On the Piedmont inselbergs, the occurrence of boulders is related to the underlying bedrock. Inselbergs composed of massive rocks are boulder covered, whereas those on foliated rocks tend to have few boulders. Both Big Cobbler Mountain and Buck Mountain are examples of boulder-covered inselbergs. In both cases the boulders are not confined to the side-slopes, but can also be found as boulder fans on the adjacent piedmont surface. Farther south on the Piedmont, massive rock inselbergs visited in southern North Carolina and South Carolina have boulder covered slopes that extend down only to the piedmont angle.

Cobble and pebble fragments on the inselberg slopes are generally incorporated into the regolith cover and are covered by a vegetation layer that acts to protect the surface against erosion. Because fragments are not loose or exposed, there is little movement downslope by wash processes. Large rock fragments are found on the surface near bedrock outcrops and in areas where the vegetation cover is absent. In the latter case, some winnowing of fine material, probably by surface wash, has occurred and pebbles are concentrated at the surface.

An analysis was made to determine if there was any variation in grain size (ranging from pebble to clay) related to either distance downslope or slope angle (Kesel, 1972). According to these data, there is no orderly change in the size of material on the inselberg side-slopes. Similar conclusions concerning these relationships are also reached by Ahnert (1970a) for crystalline rocks in North Carolina and by Furley (1968) in England. Some variations in the proportions of the size classes appear to be related to the underlying bedrock type. The waste cover on slopes formed on high foliated rocks (Lookadoo and Six Miles mountains) has a much higher percentage of sand than on massive rocks. The waste cover on massive rocks contains a higher porportion of silt and clay. The amount of variation in the coarser material seems to be greater on slopes where the bedrock has numerous outcrops (e. g., Big Cobbler Mountain) or has considerable lithological heterogeneity (e. g., Six Mile Mountain). On Big Cobbler, for example, the concentration of pebbles is quite high near bedrock outcrops and then tends to decrease rapidly away from it.

Some slopes show a decrease in coarse material from the side-slope to the adjacent piedmont slope. In the case of the Six Mile Mountain slope, the break in material size occurs near the piedmont angle. On the slopes of Buck and Big Cobbler mountains, it occurs at a considerable distance downslope from the piedmont angle. These differences could indicate progressive comminution of slope debris because of mass wasting or, possibly, sorting because of surface wash. However, most of the piedmont surfaces examined have undergone such extensive erosion as a result of cultivation that much of the sediment data cannot be relied upon.

At several locations samples of the waste cover were taken from depths to 18 inches. In each case there is an increase in the percentage of clay downward in the waste cover. This increase, along with clay skins observed on soil peds in these lower horizons, indicates that clay material is being eluviated and moved down through the waste cover.

An analysis was made to determine if any changes occurred in the degree of roundness of the coarse sand fraction along the slope profile. Two hundred grains were selected at random and examined under a low-power petrographic microscope. The roundness was assessed using the method suggested by Muller (1967, p. 100), which ranks the grains into five categories, ranging from angular to well rounded. Three of the four inselberg slopes were analyzed in this manner. The variation in the degree of roundness does not change significantly over the slope profile. The greatest variation occurs on the Big Cobbler Mountain slope and is probably related to the amount of surface exposure of the bedrock. The other two slopes have a continuous waste cover and exhibit less variation in grain roundness.

The amount of feldspar and quartz in this material was determined by using the staining method previously. The variation in mineral content is greatest on slopes of Big Cobbler and Six Mile Mountains, probably as the result of changes in the mineral composition and the amount of surface exposure of the bedrock. The North and South Carolina slopes exhibit a higher proportion of quartz than Big Cobbler Mountain, which explains the greater amount of sand size material on the former two slopes. In each profile the minerals in the waste cover that are most susceptible to chemical weathering have been removed. For example, plagioclase feldspar accounts for 33 percent of the mineral composition of the bedrock underlying Big Cobbler Mountain, but it is absent from the fine material (Kesel, 1972). Similar trends are also apparent on the other slopes.

Several samples were also taken from the upper six inches of gully bottoms on the inselbergs and subjected to granulometric analyses. Although the number of samples is not large, it does give some indication of the material transported to the drainage way from the adjacent piedmont and inselberg slopes.

The gullies on the Piedmont inselbergs have a thick vegetation cover, giving the impression that they are undergoing a little surface erosion. The analysis of gully samples indicates that there is a difference in the size of material taken from the gully bottoms and that taken from the adjacent inselberg slopes (Kesel, 1972). Samples taken from the Big Cobbler Mountain slope show a sizable increase in the sand fraction. Similar samples taken from Lookadoo Mountain show an increase in the silt content. These increases can be accounted for, in part, by the relative decrease of the small gravel and clay fractions. The lower proportion of small gravel in the gully channels probably results from the lack of movement of these fragments on the inselberg slopes. There is a decrease in clay because of eluviation by seepage water, however, it is not sufficient to account for the entire increase in silt and sand in the gully samples. Sand and, in the case of Lookadoo Mountain, silt must be transported to the gully channel by surface wash running through the thick vegetation cover on the adjacent slopes.

The amount of feldspar and quartz and the degree of roundness of particles were also examined. The data indicate no differences between the slope and gully materials. This would seem to be the expected result, for this material has probably traveled only a short distance from the interfluve to the adjacent gully.

INSELBERG FORMATION

The formation of inselberg landscapes must be considered on two levels. First, there are several prerequisites necessary for the development of the inselberg landscape and, second, there are the processes that produce the morphologic characteristics of the individual inselbergs.

The models of landscape development that have been applied to the Piedmont (Davis, 1922, 1932; Hack, 1960) do not adequately explain the inselberg landforms. The description offered by Davis of monadnocks in a humid temperate region is not consistant with current observations. A comparison of the slope profiles and the steepest slope segment measurements on Piedmont inselbergs in this report, with similar data from inselbergs in different climatic areas, indicates that there is little correlation between these forms and climate (Kesel, 1973). The data presented previously (Table 1) indicate that side-slope profiles of the erosional remnants are not predominantly convex but have a basal concavity that forms up to 30 percent of the profile. The upper convexity accounts for only 11 to 23 percent of the profile. Side-slopes are far from gentle and gradients up to 30 degrees are not uncommon. In addition the break-in-slope at the base of the inselberg was not found to be as conspicuous a feature in the humid regions as it is in arid ones, but it was not the gradual form envisaged by Davis (Figure 6). Davis seems to have realized that these deficiencies existed in his model. In 1930 he clearly incorporates elements of slope retreat in the sequence of slope development in humid areas. His diagram (Davis, 1930, figure 7) of the final stage of the erosion cycle is composed of concave piedmont (or pediment-like) surfaces from which steep-sided erosional remnants rise abruptly. The erosional remnants in this figure correspond very closely to the inselbergs on the Piedmont.

Hack's ideas are equally difficult to apply to Piedmont inselbergs. In order to have a uniform rate of downwasting, it is necessary to have a continuous, uniform rate of uplift. Except for possible faulting during the Triassic (Stucky, 1965) and the Tertiary (White, 1950) and recent local warping (Richards and Judson, 1965), there is little evidence for such uplift within the Quaternary. A landscape that has undergone a long period of quiescense is not considered in Hack's model. But even more critical, the model assumes that, during downwasting, inselberg and escarpment slopes are fixed in space by geologic contacts (Hack, 1960, p. 94). If this assumption was true, all the inselbergs and ridges on the Piedmont would be composed of more resistant rock than the surrounding surface. The break-in-slope (piedmont angle) between the inselberg or ridge side-slope and the adjacent erosion surface would also correspond to the contact between weak and strong rocks. The map evidence in this report does not support either corollary. These data indicate a number of cases that the lithologic boundary lies some distance out from the base of erosional remnants which seems to imply a form of lateral slope replacement.

It is suggested that the major prerequisites for inselberg formation is sufficient relief, created either by tectonic activity or incision of the major river systems, followed by the lateral replacement of scarp slopes or the valley side-slopes.

With the possible exception of the Blue Ridge escarpment, most of the Piedmont relief occurs as the river network cuts down. Local uplift has caused increased erosion along the Blue Ridge, forming the numerous spurs that extend from the escarpment. It has also resulted in the detachment of the mountain masses on the Piedmont in Virginia and North Carolina. In North Carolina, for example, the Catawba and Yadkin Rivers flow southeastward from the Blue Ridge and Piedmont across the only portion of the Coastal Plain (Cape Fear Arch), which has undergone extensive erosion (Geologic Map of United States, 1932, U. S. Geol. Survey, 1:2,500,000). The overlying Tertiary material of the Coastal Plain has been stripped off, exposing the Cretaceous sediments below. It is likely that local warping along this portion of the Coastal Plain during the middle or late Tertiary (Richards and Judson, 1965) has caused increased denudation of the drainage areas of these rivers and also has accelerated headward erosion of their headwaters into the then more extensive Blue Ridge highlands. This has resulted in the numerous mountain masses that are now separated from the Blue Ridge by these river systems. The inselbergs of the Uwharrie Mountains in the Carolina Slate Belt appear to be the result of dissection by the Yadkin-Peedee River.

The role of base level as a control in the reduction of a mountain mass to a surface surmounted by inselbergs has long been a subject of debate. King (1962, p. 145) considers this reduction to be independent of base level. Penck (1924, p. 195) argues that the base level of erosion must be stable for a long period, whereas Willis (1934) emphasizes a lowering base level as a result of uplift.

After uplift and incision of major drainage lines, further development of the inselberg landscape depends on slope evolution. Do these slopes evolve due to some form of downwearing, downwasting, or lateral replacement? With lateral replacement there is retreat of the steep slope segment and replacement from below by gentler slopes, causing the lower portion of the profile to become occupied by a concavity. During evolution the slope profile may also undergo shortening because of erosion and mass wasting along the upper portion.

The uniformity of the gradients of the steep inselberg slope segments on the Piedmont suggests that the side-slopes have maintained fairly stable gradients during their evolution. King (1962, p. 145) indicates that in order to have slope replacement, slopes must maintain a critical relief. Field data seem to indicate that there is critical relief below which slopes may decline or downwaste. For example, the slopes of the larger inselbergs in the vicinity of Buck Mountain and the Blue Ridge escarpment, to the west, all have equivalent gradients. Several smaller inselbergs in the same area that are composed of the same rock type as the larger inselbergs, have slopes with lower gradients. These observations can only be considered preliminary because of the limited data. In order to determine more precisely the interrelationship between the critical relief, the slope profile, and rock type,

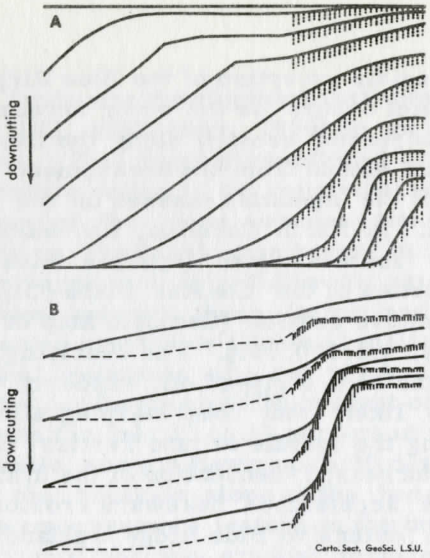


Figure 7. Development of inselberg-like profiles. A) by processes of chemical weathering and simple wash; B) by processes of chemical weathering and complex wash. Vertical lines represent more resistant rock; dashed line is base of regolith (from Ahnert, 1971, p. 151-153).

larger numbers of measurements will be required.

Further evidence for lateral replacement includes: the lack of coincidence between the break-in-slope at the base of hillslopes and lithologic contacts, and the concavity at the base of the inselberg side-slopes, which seems best explained by some degree of retreat of the steep segment. A basal concavity resulting from slope decline could be associated only with conditions of impeded basal removal; field observations presented in the succeeding section do not warrant this conclusion.

Some of these ideas support the theoretical slope evolution studies conducted by Ahnert (1971), using computer models. Several of the models (Ahnert, 1971, p. 151-153) exhibit characteristics similar to inselbergs in this study (Figure 7). These models suggest the following points: (1) Each type of bedrock develops an equilibrium profile that tends to retreat more or less parallel to itself. (2) Lateral replacement of the side-slopes occurs when sufficient relief has been attained. (3) The gradient of the inselberg side slope is, at least in part, dependent on the relief. (4) Downwasting occurs on slopes with gentle gradients (e. g., piedmont slopes).

Processes on Humid Temperate Inselbergs

Weathering on humid inselbergs is mainly the result of chemical rather than physical processes. Physical weathering is limited to sheeting and freeze-thaw activity. There is little evidence to indicate that thermal expansion and contraction are important on the Piedmont inselbergs: this process is most likely the result of small diurnal temperature range.

Massive exfoliation sheets were noted on some Piedmont inselbergs and have been described in adjacent areas in the Blue Ridge (Hack, 1966) and in Georgia (Hopson, 1958). Where present (e. g., Stone Mountain, Georgia), the sheets give the inselberg a domal or convex profile. Thin (less than 0. 5 inches thick) "onionskin" sheets are occasionally visible on bedrock outcrops and boulders and probably result from chemical rather than physical processes.

Weathering because of frost action is dependent on the number of freeze-thaw cycles and the availability of moisture. Both criteria are available on the Piedmont inselbergs, and on several occasions ice needle growth was noted on exposed ground. However, there is little field evidence to indicate the degree of intensity of the process.

Chemical weathering is intense on the Piedmont inselbergs. An examination of the waste cover shows that the more easily weathered minerals, particularly plagioclase feldspar and biotite mica, have been decomposed and removed from the size fractions larger than silt. The decomposition of these minerals is, presumably, the source of the clay size material in the waste cover (Wolff, 1967) Additional characteristics of the humid waste cover that reflect intense weathering are the high percentage of clay, the lack of gravel-size fragments, and the high degree of rounding of fragments. The degree of rounding of fragments in the humid waste cover is mainly the result of chemical weathering rather than transport processes. The thick waste cover on the humid inselbergs has developed because the rate of weathering on the sideslopes has exceeded the rate of removal, although this relationship need not still be true. The thickness between inselbergs varies because of differences in rock type and structure. The regolith cover on the Piedmont inselbergs also acts as a cover to retain moisture and, in turn, this increases the differential weathering of the underlying bedrock surface. This creates greater irregularities of the bedrock surface and is probably the reason for variations in the waste-cover thickness (Figure 6). It also helps to explain the complex profiles of the humid inselbergs.

The waste cover on the humid piedmont slopes is generally thought to result from "in situ" weathering. On the foliated rocks, the waste cover on the piedmont surfaces is quite deep, exceeding 100 feet in many places (Figure 6). The waste cover on piedmont surfaces on massive rocks is much thinner, except where structural conditions such as joints permit deeper weathering. The bedrock surface beneath the waste cover on three of the piedmont slopes examined had concave profiles similar to the surface profiles (Figure 6). There is no evidence to indicate that this bedrock surface was formed by running water and then was subsequently buried by the deposition of material by fluvial processes. An examination of the waste covers on these surfaces reveals no evidence of layering or sorting as would be expected if the material had been carried and deposited by fluvial processes. The waste cover on the three piedmont surfaces has a fairly constant thickness downslope, which seems to indicate that there is uniform weathering and downwasting of the piedmont surface. The control of these surfaces by fluvial processes is suggested by the similarity between the profiles of the interstream areas of the piedmont surface and the ephemeral channels that act as the local base level for these areas. There is a strong resemblance between the concave piedmont surfaces and the etchplains described by Wayland (1933) and the double planation surface of Budel (1957). Essentially these surfaces result from degradation of the interstream areas by slope processes, particularly surface wash (Budel, 1957).

The major processes that transport material downslope on the Piedmont inselbergs are mass wasting, surface wash, throughflow, and gullying. Mass wasting includes freeze-thaw activity and movement related to the vegetation cover. The former is associated with the growth of ice needles on exposed surfaces and within the organic layer of the soil cover. The relative importance of the process is restricted by the limited frequency of freeze-thaw cycles. The latter process has been termed floral pedoturbation and is the result of trees falling over. The process, although limited in extent, can bring large quantities of rock debris to the surface, which can then roll downslope. It also exposes fine material to wash processes.

Soil creek has long been considered a major characteristic of denudation in humid temperate climates. Attempts to measure creep have produced only questionable results. There is no indication from the field and laboratory data in this study that soil creep is currently active on the slopes of the Piedmont inselbergs. These findings occur with the observations of Ahnert (1970a) that creep is either very weak or entirely absent on slopes composed of crystalline rocks in North Carolina.

Features such as the boulder fields that extend out from the base of a number of inselbergs in the northern Piedmont probably indicate that mass wasting has been more active in the past, especially at a time when freeze-thaw cycles were more numerous. Similar features have been described in adjacent areas and have been attributed to a periglacial environment during the Pleistocene period (Michalek, 1969; Clark, 1968).

Surface wash, in theory, plays only a small role in transporting debris downslope because of the thick continuous cover of leaf litter and decayed organic matter. The quantity of water available for wash is also reduced by a high rate of infiltration. An indication of the extent to which surface wash has occurred may be the high proportion of sand and silt size material in the gully bottoms. The source of this material is the surface horizon of the soils derived from the weathering of the bedrock. Wash processes move this material through the litter cover toward the gullies.

A substantial proportion of the precipitation that falls on the Piedmont inselberg slopes infiltrates and flows downslope through the waste cover as throughflow. The effectiveness of throughflow as a method of transporting debris downslope through the interstices of the regolith cover has been described by Burykin (1957). The importance of throughflow as a method of transporting material through the waste cover on the humid inselberg slopes is uncertain. The alluvial clay horizon, along with clay skins on the soil peds in the regolith, indicates that such movement does occur. However, there is little evidence of increased clay and silt content downslope as would be expected if throughflow were effective. Where the waste cover is discontinuous, throughflow emerges along contact zones and debris is transported by surface wash. Spring sapping along the slope foot has been suggested as an important process in the evolution of the Piedmont slopes (Birot, 1952, p. 149) although sufficient field evidence has not been found to support this idea. Water movement within the regolith is also important by removing material in solution. The amount of dissolved material removed by this water has been estimated by Cleaves and others (1970), from the study of a forested watershed on the Piedmont, to be five times as effective in removing material as is surface erosion.

Deep, parallel to subparallel gully channels are common on all the Piedmont inselbergs. It was noted previously that most of the flow in these channels is intermittent. A number of the gullies on the inselbergs appear to be less active presently than they were in the past as a result of decrease in the quantity of water available for erosion. Such a reduction in flow could have resulted from the detachment of the inselberg from a large mountain mass or from lower infiltration and greater runoff because of increased frost action during the Pleistocene. These gullies seem to be undergoing only minor erosion under the often heavy rains of the present climate. During visits to the inselbergs over a period of 18 months, there was little disturbance to the litter cover in the gullies at times of fairly intense rainfall. Dams across several of the gullies created by fallen trees show only minor buildup of litter and sediment. Prior to the start of fieldwork on the Virginia inselbergs, the area of northern Virginia was struck by Hurricane Camille in 1969. The rainfall intensity (27 inches in 24 hours) associated with this storm had a return interval that was in excess of 1,000 years (EDS, 1969, p. 458). An examination of aerial photographs taken of northern Virginia immediately after the storm indicates that many of the gullies had experienced intense erosion (Va. Div. Min. Res., 1969). It would appear that the processes responsible for the erosion of these gullies are high intensity events of low frequency. This is in agreement with the observations of Hack (1956) and the measurements of Ireland and others (1939). The gullies tend to extend themselves upslope by erosion of springs and soil seeps around the gully heads. In places where the gullies turn transverse to the slope profiles (e. g., Lookadoo and Six Mile mountains, Figure 6), the cause undercutting and steepening of the slope above. Bryan (1940) and, more recently, Beaty (1959) have emphasized the importance of gully erosion in the retreat of regolith-covered slopes.

CONCLUSIONS

The principal results of this study include the following:

1. The necessary prerequisites for the development of the inselberg landscape are sufficient relief created by tectonic activity (e.g., fault scarp) or incision of the major river systems followed by a period of crustal stability. This latter factor is necessary to allow lateral replacement of the mountain escarpment or the inselberg side-slopes. The lateral replacement of slopes also seems to depend on the maintenance of a critical relief. Slopes below the critical relief or with gentle gradients tend to downwaste.

2. The inselbergs on the Piedmont can be loosely grouped into four types: (a) outliers in front of a mountain mass escarpment; (b) detached segments of linear ridges; (c) dissected mountain masses, and (d) completely isolated types. The inselbergs that have been detached from mountain scarps and are still in close proximity to the scarp are generally composed of the same rock type as the adjacent piedmont surface. Most of the inselbergs that are farther from the scarps are composed of more resistant rock types.

3. Structural conditions were found to be important factors in determining the morphology of the inselbergs. Joint direction and density are important in the orientation and resistance of the inselbergs. The dip, strike, and thickness of lithologic units help to determine the size and orientation of the inselberg.

4. The inselberg landform elements, including the side-slope profile, the piedmont surface, and the piedmont angle, exhibit differences that are related to the underlying rock type and to the climate. The slope gradients on massive rocks are steeper than on foliated rocks. The piedmont angle at the base of the humid inselbergs is a concave surface developed on the regolith cover. The concave profiles of this surface are the result of the numerous gullies that traverse the side-slopes and the piedmont surfaces. The gullies have concave longitudinal profiles that act as the local base level for the adjacent interfluves and give rise to the concave erosion surface at the base of the inselbergs.

5. The seismic profiles suggest that changes in thickness of the waste cover on humid inselberg slopes are greatly influenced by the

composition and structure of the underlying bedrock.

6. An analysis of the waste cover debris indicates that the breakdown of crystalline rocks of the Piedmont inselbergs is brought about by the weathering and removal of less-resistant minerals, particularly plagioclase feldspar and biotite mica. Intense weathering of this material is reflected by the high clay content, few gravel-size fragments, and the high degree of rounding of these fragments. Within the waste cover, there is little suggestion of an orderly downslope change in the range of particle size.

7. The major process on humid inselbergs are chemical weathering, throughflow, solution, overland flow, and gullying.

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POSSIBLE NEW MAJOR FAULTS IN THE PIEDMONT OF NORTHERN DELAWARE AND SOUTHEASTERN PENNSYLVANIA AND THEIR RELATIONSHIP TO RECENT EARTHQUAKES

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ABSTRACT

Study of ERTS-1 imagery, stream characteristics, foliation, and aeromagnetic data shows that a number of previously unknown major lineaments exist in the area of northern Delaware, southeastern Pennsylvania, and adjacent portion of New Jersey. Some of these lineaments are interpreted as faults on the basis of their similar appearance with the known faults on the ERTS-1 imagery, partial correspondence of several lineaments with the known faults, characteristics of stream patterns, truncation of drainage divides, aeromagnetic lineaments, and displacement of rock units along some lineaments.

No direct relationship between the newly discovered faults and the recent earthquakes in northern Delaware and southeastern Pennsylvania has been conclusively established. The earthquakes did not cause any significant surface deformations. This may be the result of a deep burial of the active fracture zones so they do not directly intersect the surface, low energy level of the earthquakes, or the strain that has been continuously building up has not yet reached the rupture level at the surface.

The northeast-southwest trending set of faults extending from Delaware through southeastern Pennsylvania to New Jersey generally corresponds to a postulated major Appalachian crustal wrench-fault zone.

INTRODUCTION

The strongest earthquake known to have occurred in northern Delaware and the surrounding area took place in 1871 and had an estimated intensity of VII. Small tremors have been reported from time to time which seem to have increased both in frequency and intensity in recent years. The earthquake of February 28, 1973 had a magnitute of

3.8 and a maximum intensity of VI (Woodruff et al., 1973) This earthquake was felt in a relatively large area encompassing parts of Maryland, Pennsylvania, Delaware, and New Jersey. The epicenter was located near Wilmington, Delaware and the focus was believed to be less than 10 kilometers below the surface (Woodruff, et al., 1973).

Northern Delaware, where the earthquake was felt most intensely, is a part of the deformed crystalline belt of the Appalachian Piedmont Province. The core of the belt is made up of Precambrian gneisses, migmatites, and amphibolites comprising the Baltimore Gneiss. These are overlain by younger crystalline and metasedimentary rocks. To the north of the deformed belt is the Newark-Gettysburg Triassic Basin filled with sedimentary rocks, basalts, and diabase sills and dikes (Figure 1).

There are several major faults known in this region (Figure 1), however, none in Delaware. For this reason the immediate earthquake area has been investigated to determine if there are structural elements, faults in particular, that might be related to the earthquakes.

Acknowledgments

I wish to express my appreciation to Maria L. Crawford and William A. Crawford, Department of Geology, Bryn Mawr College, Mary Emma Wagner, Geology Department, University of Pennsylvania, and Robert R. Jordan, Delaware Geological Survey for many beneficial discussions of various aspects of the study. I also thank William D. Carter, EROS Program, U.S.G.S. for help with the interpretation of the ERTS-1 imagery.

METHOD OF INVESTIGATION

Study of ERTS-1 Imagery

Several major lineaments are observed on the ERTS-1 imagery (Figure 1). They generally trend north-south, northeast-southwest, and northwest-southeast, appear to be unaffected by topography, rock types, stratigraphic relationships, known structural boundaries and structural elements, and locally have rock displacement associated with them. At least three of the lineaments correspond with known faults, or portions of the known faults.

The lineaments are usually straight, although some are slightly curved, and are considered to be surface expression of vertical or nearly vertical fracture zones (Mollard, 1957; Lattman and Parizek, 1964; Parizek, 1971).


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Newark
Allentown
TRIASSIC
BASIN
Trenton
offset
DEFORMED
CRYSTALLINE
Philadelphia
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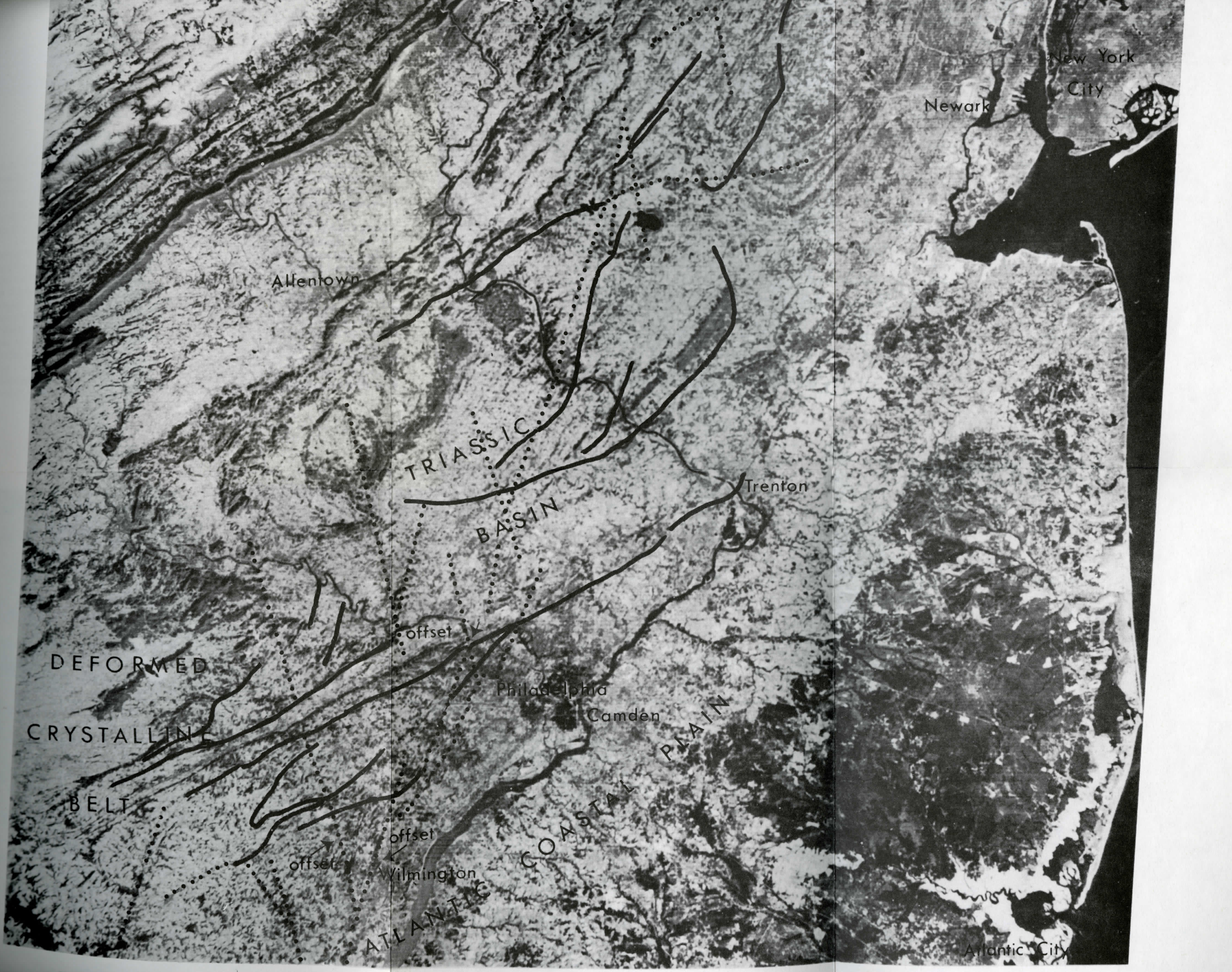

Figure 1 ERTS-1 imagery of southeastern Pennsylvania, northern Delaware, and New Jersey.
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Study of Stream Patterns

Most of the lineaments observed on the ERTS-1 imagery can also be recognized in the drainage patterns (Figure 2). Many streams crossing the lineaments abruptly change their courses and for some distances are aligned with the lineaments. Such streams are usually accompanied by truncated drainage divides.

Several asymmetric drainage basins with major streams having tributaries on one side only can be seen in the eastern part of the immediate earthquake area (Figures 2 and 3). At least two such basins are also observed in the western part of the area in the lower reaches of Red Clay Creek (Figure 2). Many streams have pincer like upper reaches, although they are not apparent at the map scale.

Study of Aeromagnetic Data

There are several distinct magnetic lineaments in the area (Figure 4). The most prominent one is a northeast-southwest trending long and narrow lineament extending toward the Triassic Basin to the north and the Coastal Plain to the south. Various other long lineaments are seen to the east and west of it trending approximately in the same direction. The close correspondence between the ERTS-1 and magnetic lineament a-a (Figure 4) is clearly seen.

DISCUSSION

Several different lines of evidence (ERTS-1 imagery, stream characteristics, and aeromagnetic data) suggest that some of the major lineaments could be faults that have been previously unknown. This conclusion is based on the similar appearance of the lineaments with the known faults, their expression in the stream patterns, truncated drainage divides, offsets of rock units, and pronounced aeromagnetic anomalies associated with some lineaments.

Possible right-lateral offsets are indicated at several places along the long northeast-southwest trending set of lineaments. For example, at the Schuylkill River, where the lineaments cross the carbonate belt, both the river and the carbonate rocks seem to be displaced in the same manner (Figure 1). A similar strike-slip is observed along Brandywine Creek in northern Delaware (Figures 2 and 5); here the drainage divide is truncated in the same direction as well. The "stretched-out" magnetic anomalies (magnetic lineaments) corresponding to the ERTS-1 lineaments could have also been produced by such a deformation (Figure 4). A major right-lateral fault is also implied by the characteristics of the foliation. In the western part of the area the foliation attitude is aligned with the regional Appalachian structural trend, has a dominant control over the orientation of major tributary

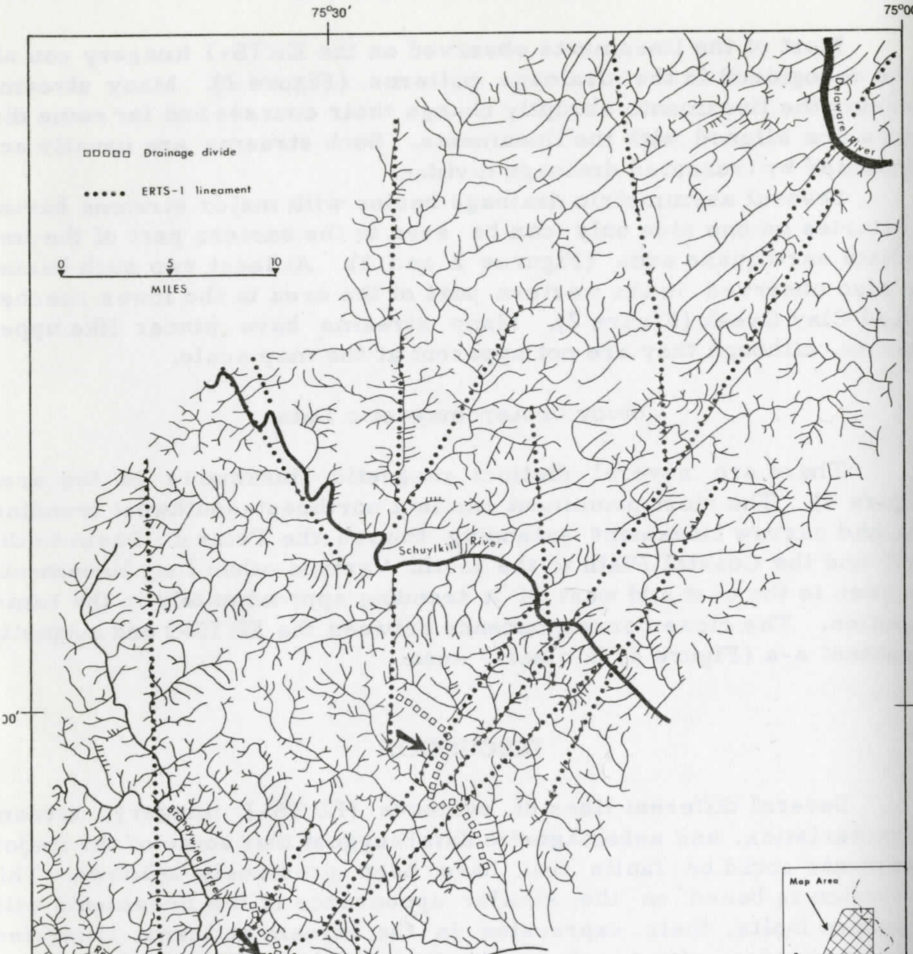

Figure 2. The drainage systems in northern Delaware and southeastern Pennsylvania (taken from U. S. Geological Survey topographic maps 1:62,500). The alignment of some stream channels with the major ERTS-1 lineaments (dotted lines) is apparent. The arrows point to the major truncated drainage divides. The numbers refer to the asymmetric drainage basins in the immediate earthquake area.

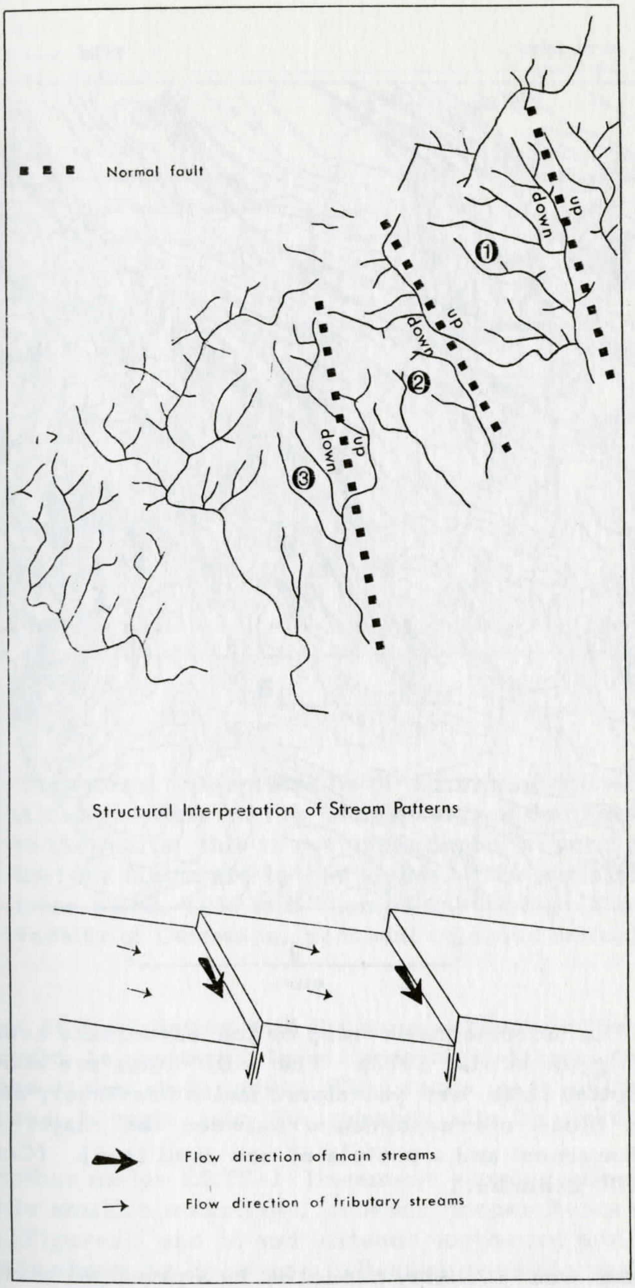

Figure 3. The asymmetric drainage basins in the immediate earthquake area are interpreted as being developed on faulted blocks. The main streams flow along the faults while the tributaries flow over the faulted blocks.

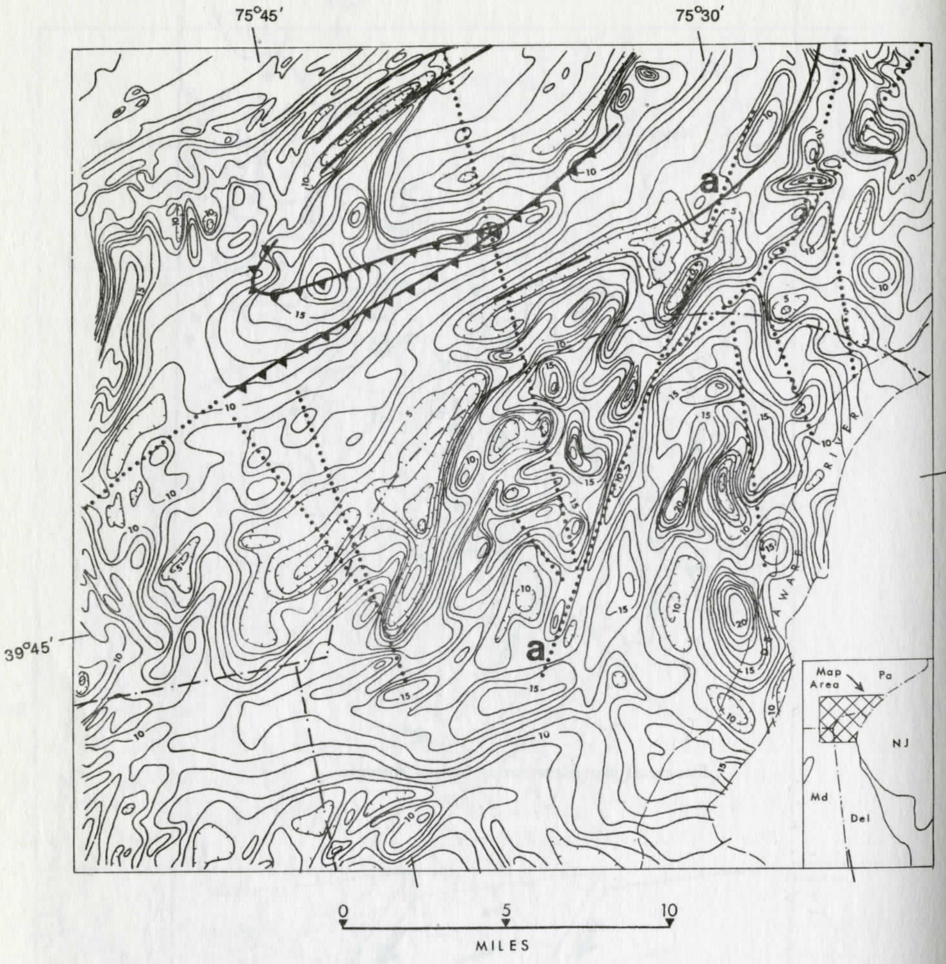

Figure 4. The aeromagnetic map of the earthquake area (taken from Higgins et al., 1973). The solid lines are known faults; the dotted lines are postulated faults previously unknown. Note a close correspondence between the major aeromagnetic lineament and a postulated new fault (a-a). (Contour interval 100 gammas.)

streams, and was probably produced by a principal north-south compressional stress (Figure 5).

In the central and eastern parts of the area the foliation attitude makes an angle of about 40 degrees with the Appalachian structural trend and has little or no control over the stream orientation (Figure 6). This remarkable deviation from the regional structural trend and

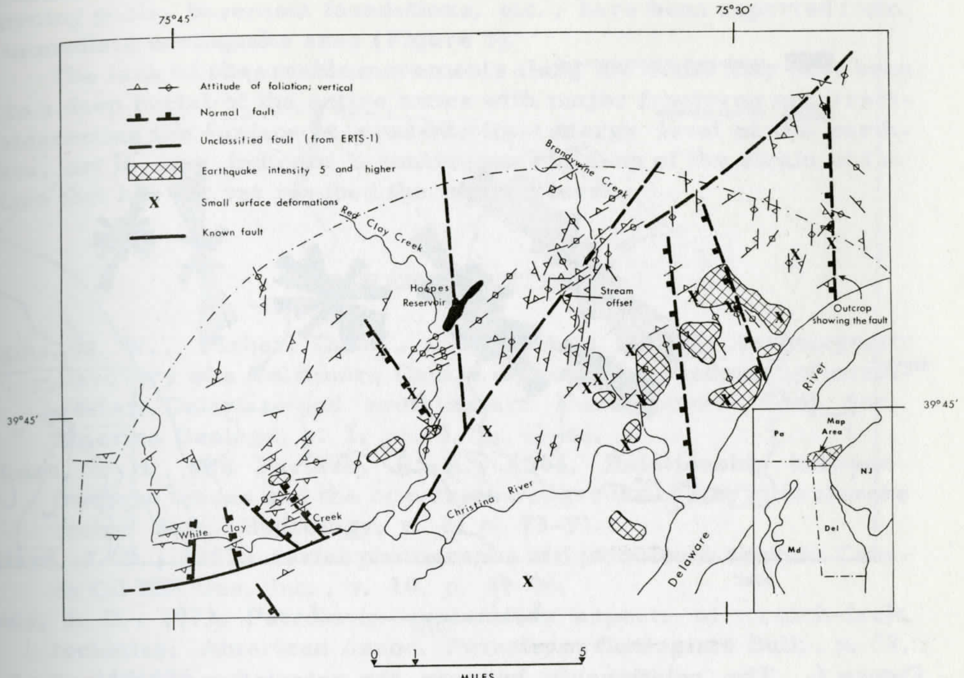

Figure 5. Structural interpretation of the immediate earthquake area. Although some of the small surface deformations fall close to the faults, this is not considered a conclusive evidence that the faults are indeed active at the surface (foliation taken from Ward, 1959 and Thompson, Geology Department, University of Delaware, personal communication).

the absence of the foliation with the same attitude in the western part of the area could be explained by a major right-lateral fault dividing the two portions of the study area. The rocks east of the fault could be allochthonous, brought into the present site by movements along the fault.

Another major ERTS-1 lineament showing offset, although of a significantly smaller magnitude, crosses Hoopes Reservoir in northern Delaware (Figures 1 and 5) and extends northward into Pennsylvania. The offset is shown by lineations indicating possible rock displacements (Figure 1). However, because of its small magnitude, it is not clear whether it resulted from a lateral or vertical movement.

The asymmetric drainage basins in the immediate earthquake area are believed to have been developed on a series of faulted blocks. The main streams flow along the fault planes while the tributaries flow

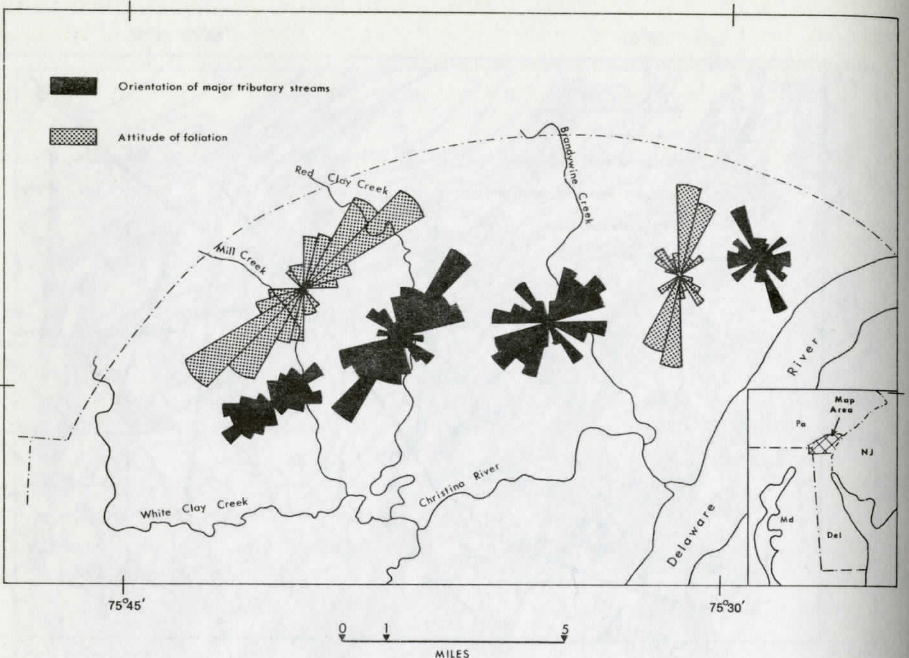

Figure 6. The relationship between the orientation of the major tributary streams and the attitude of foliation. The control of the foliation on the tributaries in the western part of the area is quite apparent. In the vicinity of Brandywine Creek and to the east of it such a control is slight or nonexistent.

over the faulted blocks (Figures 2 and 3). The flow direction of the tributary streams suggests that the blocks also tilted southeastward. One of the faults has since been found in the field in the road cut for the construction of the Interstate Highway 95 northeast of Wilmington, Delaware (Figure 5).

CONCLUSIONS

The northeast-southwest trending set of lineaments, most of which are believed to be faults showing right-lateral slip, generally correspond with a portion of a major Appalachian crustal wrench-fault zone postulated by Moody (1973). Although there is no evidence at present to link the recent earthquake with any of the newly discovered faults, it is reasonable to assume that the area is still tectonically active no matter how imperceptible this activity may be at the surface.

There are no significant surface deformations directly associated with the earthquakes. However, small sink holes, cracks in driveways, swimming pools, basement foundations, etc., have been reported from the immediate earthquake area (Figure 5).

The lack of observable movements along the faults may have been due to a deep burial of the active zones with major fractures not directly intersecting the surface at present, low energy level of the earthquakes, or it may indicate a continuous build-up of the strain at the surface that has not yet reached the rupture level.

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OYSTER REEF SEDIMENTATION, BILOXI BAY, MISSISSIPPI

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ABSTRACT

Size-frequency distributions were determined for bottom sediments, collected by grab, from three living oyster reefs (27 samples) and from two non-reef sites (33 samples). Oyster reef sediments were found to contain 10 percent gravel (shells), about 60 percent sand (mixture of fragmented shells and quartz), 15 percent silt and 15 percent clay. Nearby non-reef sediment contained only traces of gravel, about 35 percent sand, 28 percent silt and 38 percent clay. Size-frequency distributions of reef sediment were leptokurtic, and those for non-reef sediments were platykurtic. Grainsize parameters of mean size, standard deviation and skewness did not distinguish between reef and non-reef sediments.

Grainsize modes for sand and silt in reef and non-reef sediments were similar. Sand grainsize modes were surprisingly variable, and were found between 1.88 to 3.65Φ (0.272 to 0.080 mm) respectively. A well-developed textural inversion (mixture of rounded and angular grains) in the interval between 1.25 to 1.50 Φ (0.42 to 0.35 mm) was not detectable in size-frequency distributions. Silt grainsize modes were found at 4.25 and 6.75 Φ (0.053 and 0.0094 mm) respectively. Grainsize modes for sediment in reefs matched fairly well with grainsize modes for sediment recovered from the exterior of living and dead oyster shells in the reefs.

Measured current velocities ranged up to 0.94 ft/sec at the surface, and near bottom currents met the threshold velocity of 0.5 ft/sec for erosion and transport of fine sand. Suspended sediment loads ranged between 58 and 183 mg/1, tending to be greater down-wind in both reef and non-reef environments. Suspended sediment load varies with the wind, decreasing with decreasing wind velocity.

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INTRODUCTION

Oyster reefs grow to form bathymetric shoals of relatively great surface roughness. They accumulate sediment in at least three difference ways; (a) the oyster shells themselves, (b) the aggregate of oyster shells form a physical baffle in the manner described by Ginsburg and Lowenstam (1958) which may reduce water flow sufficiently to result in gravity settling of suspended particles, and (c) the living oysters, mussels, barnacles, bryozoans and their associates are filter-feeders, obtaining their food by actively pumping and filtering the water in which they live. Oysters physically separate organic and inorganic particles, directing organic bits into their alimentary tract, and ejecting the inorganic particles as pseudofeces, weakly bonded by mucus. These feces and pseudofeces may accumulate in the reef environment.

Environmental Setting

Five different sites were studied; (1) St. Louis Bay, a 10-square mile body of shallow brackish water north of the U. S. highway 90 bridge with no active oyster reefs; Square Handkerchief Shoal, a commercially important oyster reef in Mississippi Sound, lies three miles south of the bay mouth. Site (2) is an oyster reef in northwest Biloxi Bay, about thirty miles east of St. Louis Bay. The dimensions of the Biloxi Bay Reef are 1.5 (E-W) x 0.5 (N-S) miles. It is growing in three-foot water (mean low water datum) and is closed to oyster fishing. Site (3) is an oyster reef, about 0.3 miles long, growing on a submerged spoil bank 0.2 miles northwest of the sand spit on Marsh Point. Site (4) is a small oval oyster reef, about 30 feet in diameter, growing on a spoil bank that is emergent at low tide in Davis Bayou (Figure 1). Many growing oysters were seen on this reef in late summer 1971, but observations by diving with a face mask in early summer 1972 showed that it was now mostly dead shells. Site (5) is an oval, emergent spoil bank, 80 ft. (N-S) x 140 ft. (E-W), located 0.3 miles east of site (4) in Davis Bayou. No living oysters were seen on this spoil bank, but disarticulated oyster shells were found, about 1 shell per 10 square feet. A population of fiddler crabs (<u>Uca</u> ?) was living there which had excavated their burrows near the low water line. These crabs remove sand from their burrows by forming the grains into balls 3-5 mm in diameter. The exposed part of the spoil bank adjacent to the low water mark was covered with these sand balls. The balls were cohesive enough to be picked up by hand, but disintegrated when placed in water. Presumably these sand balls would not survive in the geologic record. Hartnoll (1973, pls. 1 and 2) has described and illustrated similar sand balls made by the crab <u>Dotilla fenestrata</u> in East Africa. The thin layer of sand covering red and yellow mud of the spoil bank in Davis Bayou was produced by the sand-quarrying of the fiddler crabs. The age of this red and yellow mud is probably Pleistocene (Otvos, 1972, Fig. 2, p.

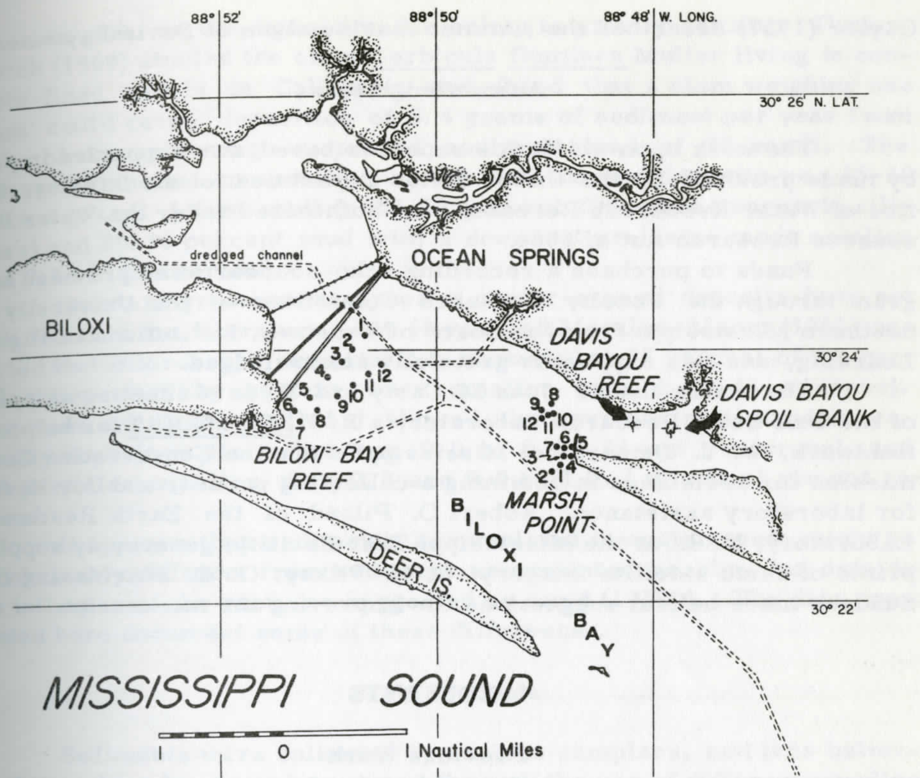

Figure 1. Index map of Biloxi Bay area, Mississippi. Traced from U. S. Dept. of Commerce Nautical Chart 876-SC.

225; Otvos, 1973).

Location of sites (2) to (5) is shown in Figure 1. The environmental setting for St. Louis Bay was reviewed by Hoskin (1971a), and Biloxi Bay is judged to be similar, except for greater concentration of human activity in the latter. Local "bedrock" is unconsolidated red and yellow mottled sand and mud, probably of Pleistocene age. This material is covered by a layer of gray, unconsolidated silt and clay only a few feet thick, as channel dredging commonly exposes the brightly-colored underlying deposits in cuts no deeper than 6 feet. Sediment movement caused by trawling for bait shrimp, channel dredging and propeller wash was observed to occur almost daily.

Upshaw et al. (1966) published data for regional characteristics of salinity, water temperature, water circulation, water depth (see also U. S. Dept. of Commerce 1970), and a sediment map showing ratios between three grainsize components (their Pl. 3). Priddy et al. (1955) published some chemical and grainsize data for Biloxi Bay and Davis Bayou. Upshaw et al. (1966) and Priddy et al. (1955) showed that silt and clay were major components of the bottom sediment. Humm and

Caylor (1957) described the summer marine algae of Davis Bayou.

Acknowledgments

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SEDIMENTS

Previous Work

Except for Gunter and Demoran (1971) and Cullen (1962), most earlier studies of oyster-sediment relationships have involved aquarium experiments with living oysters; surprisingly, Galtsoff's (1964) review contains little data on this subject. Loosanoff and Tommers (1948) showed that increasing the amount of suspended sediment caused a decrease in the rate of water pumping by the oyster. Mackin (1956) showed that oysters were able to remove about 10 percent of the turbidity caused by adding natural mud from Bayou Rigaud, Louisiana, to the water, in the range of 100 to 700 mg/l. Lund (1957a, Table 1, p. 304) found that one oyster would produce 1. 67 cc of pseudofeces and 0. 74 cc feces (total deposited volume 2. 41 cc) per day, and that increasing the rate of flow of turbid water increased the volumes of pseudofeces and feces produced. Lund's data (1957b) showed that on a dry weight basis, one oyster could deposit 0. 82 gm of sediment per day, or between 5 and 23 percent of the suspended sediment load supplied to the oyster. The rate of oyster deposition was found to be 7. 88 greater than gravity settling, and that dead shells did not cause accumulation of sediment significantly different from that of gravity settling in the absence of shells. Haven and Morales-Alamo (1966) determined from laboratory experiments that oysters deposited 0. 23 gm of sediment per day per oyster over a 6 month period. Deposition of mud by oysters was 6 times as great as the deposition due solely to gravity settling. Prokopovich (1969) studied the clam Corbicula fluminea Muller living in concrete-lined canals in California and found that a clam weighing one gram could cause deposition of 5.4 grams of sediment per year from water having an average suspended sediment load of 30 mg/l. The average grainsize composition of the clam-caused deposits was 25-30 percent gravel (clam shells), 30-50 percent fine sand (inorganic silicates) and 20-30 percent mud with a dominant grainsize mode smaller than 7.65 Φ (5 microns).

Standard grainsize analyses of oyster-caused deposits have not been found in the literature, but Haven and Morales-Alamo (1966) reported that microscope examinations showed that 95 percent of the particles deposited by oysters were smaller than 8.4 Φ (3 microns). Jorgensen and Goldberg (1953) showed that oysters retain and subsequently deposit particles between 9.0 to 8.4 Φ (2 and 3 microns), and that particles smaller than 9.8 and 9.0 Φ (1 to 2 microns) are not retained.

It appears that sediments accumulated in oyster reefs might be recognizably different from sediment accumulated nearby, but outside the influence of the reef, as suggested by Lund (1957b). The data presented here document some of these differences.

Field Methods

Sediments were collected by various samplers, and it is believed that no bias has been introduced through the use of different sampling devices. St. Louis Bay (sampled summer 1970), Marsh Point and samples 1-4 from the Biloxi Bay Reef were Phleger cores, samples 5-12 in Biloxi Bay were taken with a Petersen grab, and samples from the Bayis Bayou Reef and Spoil Bank were scooped up by hand. The Davis Bayou samples were collected on short north-south and east-west traverses. Samples 1, 4, 7 and 10 were taken one foot seaward of the low water mark, samples 2, 5, 8 and 11 were taken 6 feet seaward, and samples 3, 6, 9 and 12 came from 15 feet seaward of the low water mark. These sampling stations are shown in Figure 1.

Suspended sediments were recovered from 5 gallon water samples taken by immersion of polyethylene bottles. Sampling stations were located in the field by horizontal sextant angles or compass traverses, and were plotted on nautical charts in the field. Sediment was stored wet, with no preservatives in polyethylene bags.

Laboratory Analysis

Wet sieving with tap water was used to separate gravel and sand (retained on a 4.0 Φ , 0.0625 mm screen) from silt and clay. The gravel and sand were oven dried and standard dry sieve analyses made at 1/4 Φ intervals. Particles passing through the dry 4.0 Φ screen were added to the wet silt and clay. Organic matter and aggregates were destroyed by digestion with H_2O_2, and standard pipet analyses made for the mud fraction (Folk, 1968). Cumulative curves were plotted on arithmetic paper, grainsize components determined, descriptive statistical parameters computed based on the Folk and Ward (1957) formulas, size-frequency curves drawn by construction (Folk, 1968, p. 42-43), and grainsize names assigned after Folk (1954).

Grainsize Components

Results of grainsize analyses for St. Louis Bay are reported in Hoskin (1971a, Table 2, p. 19-20) and for the Biloxi Bay - Davis Bayou area in Hoskin (1972, Table 1, p. 3 -31); these data are also shown as size-frequency distributions, Figures 2-7.

Gravel. Particles larger than - 1. 0 Φ (2. 00 mm) are gravel, and with one exception, gravel from this area is composed of calcium carbonate shells, mostly oysters. Most samples from the reef in Biloxi Bay (Figure 3), Marsh Point (Figure 4) and Davis Bayou (Figure 5) contain gravel, Because individual samples were only a few hundred grams, accurate size data for the gravel fraction are lacking. The average size of 33 living "mature" oysters from the Marsh Point reef was -6. 1 Φ (70 mm). Average gravel content of the three reefs sampled was about 10 percent. Areas not supporting oyster reefs contain little gravel; the average gravel content of St. Louis Bay (Figure 2) and Davis Bayou Spoil Bank (Figure 6) sediments was less than 1 percent. Gravel from the Davis Bayou Spoil Bank was composed of ironstone concretions, probably of Pleistocene age.

Sand. Sand from this area contained two components; (1) detrital quartz grains which occur mainly in the size range between 1. 0 to 4. 0 Φ (0. 5 to 0. 0625 mm), and (2) fragmented calcium carbonate skeletons of oysters, other mollusks, barnacles and encrusting bryozoans. The carbonate skeletons contribute particles in a continuous spectrum from the largest gravel down to about 1. 0 Φ (0. 5 mm). The change in sand composition from carbonate to quartz can easily be detected in Figures 2-7 as the greatly increased slope of the size-frequency curves at 1. 0 Φ .

In the Biloxi Bay area, waves are small and do not form surf, except during storms. Interestingly, a large portion of the carbonate shells in these sediments are broken. If the shells are not broken by waves, what process is responsible? In the rock record, geologists might interpret broken shells in terms of waves, whereas biological comminution is probably the main cause. McDermott (1960, Figure 3, p. 206) has shown that a mud crab, Panopeus herbsti, has broken oyster shells up to 54 mm long. Menzel and Hopkins (1956) have shown that the stone crab, Menippe mercenaria, can break the largest oysters, and these investigators estimated that 3 to 12 percent of all "planted" oyster were killed by stone crabs in Louisiana. Menzel and Hopkins

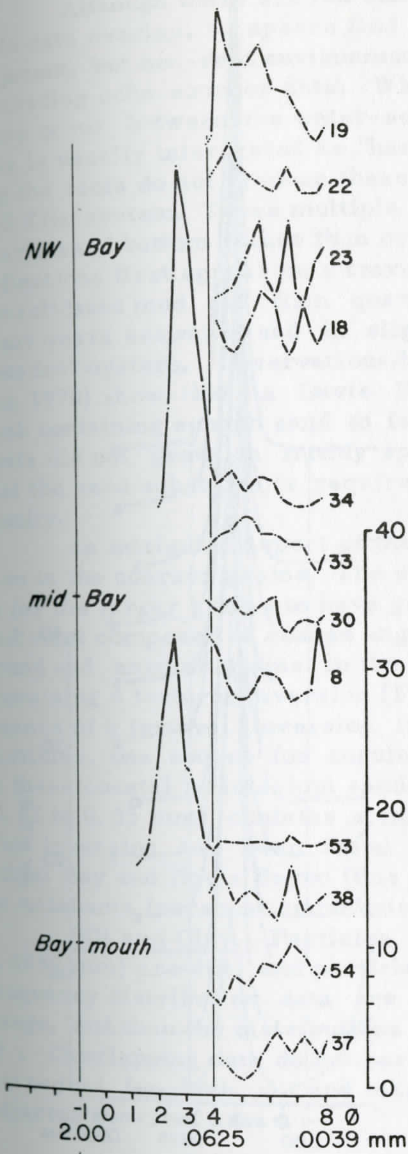

Figure 2. Size-frequency distributions for selected bottom sediments from St. Louis Bay, Mississippi.

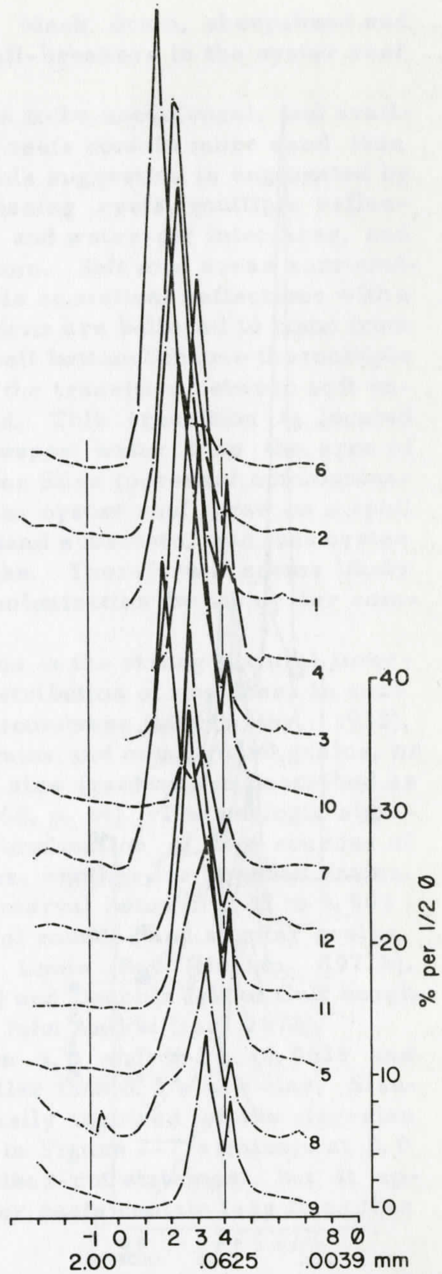

Figure 3. Size-frequency distribution for bottom sediment from the Biloxi Bay Reef.

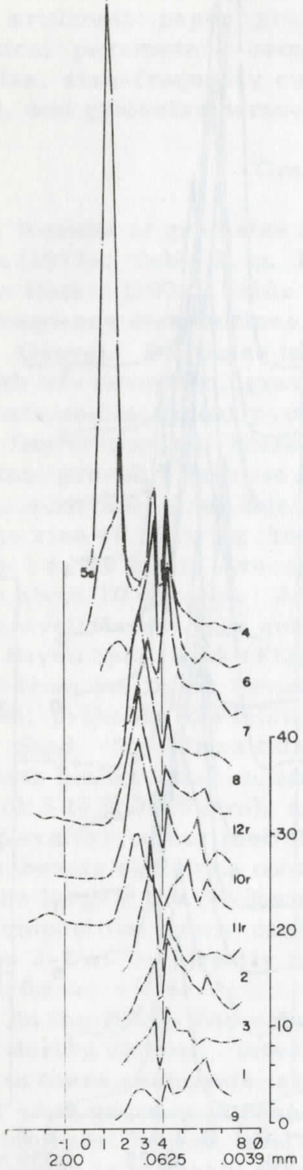

Figure 4. Size-frequency distributions for bottom sediments from Marsh Point; "s" denotes sand spit, "r" denotes oyster reef.

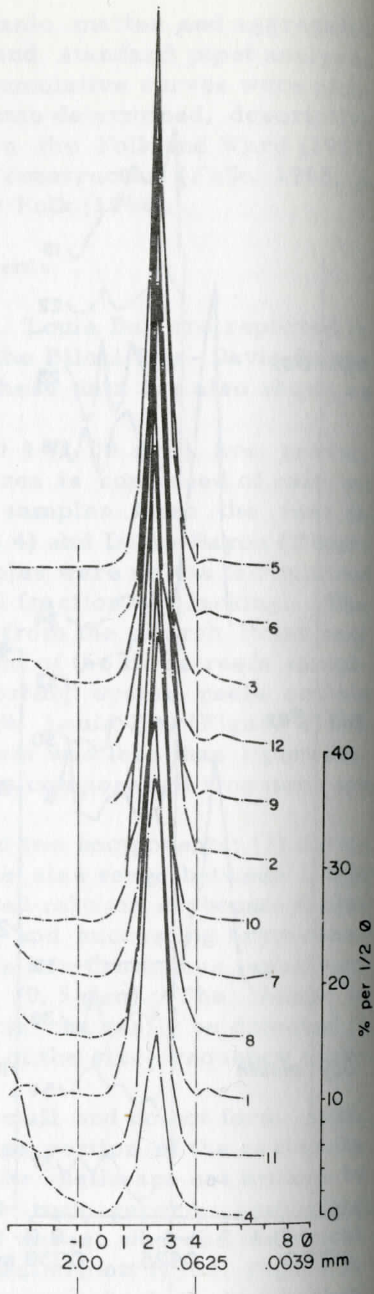

Figure 5. Size-frequency distributions for bottom sediment from the Davis Bayou oyster reef.

(1956) also suggested that the fishes, black drum, sheepshead and skates, among others, are important shell-breakers in the oyster reef community.

Although there are not enough data to be unequivocal, and available data overlap, it apears that oyster reefs contain more sand than adjacent, but non-reef environments. This suggestion is augmented by recording echo-sounder data. When crossing reefs, multiple reflections occur between the water-sediment and water-air interfaces, and this is usually interpreted as "hard" bottom. Soft mud areas surrounding the reefs do not produce these multiple acoustical reflections with a 200 KHz system. These multiple reflections are believed to come from quartz sand bottom rather than oyster shell bottom because the multiple reflections first appear on a traverse at the transition between soft unconsolidated mud and firm quartz sand. This transition is located many years seaward, and in slightly deeper water than the area of abundant oysters. Observations by Walter Siler (personal communication 1970) show that in Davis Bayou, an oyster reef grew on a spoil bank containing enough sand to form a sand substrate, and that oyster reefs did not grow on muddy spoil banks. Therefore it seems likely that the sand substrate is required for colonization by the oyster community.

An intriguing aspect of these sands is the strong textural inversion in the coarser grains. The usual distribution of roundness in sand is for the larger grains to have greater roundness (MacCarthy, 1933). Sediment composed of coarse angular grains and small round grains, or round and angular grains in the same size fraction are described as containing a textural inversion (Folk, 1968, p. 14). The geologic significance of a textural inversion is the implication of two sources of particles, one source for angular grains, another for rounded grains. In these coastal Mississippi sands, the interval between 1.25 to 1.50 Φ (0.42 to 0.35 mm) contains a mixture of rounded and angular grains. This inversion has been found in St. Louis Bay (Hoskin, 1971b), Biloxi Bay and Davis Bayou (this report) and Dauphin Island Gulf beaches, Alabama (personal communication, John A. Phillips, 1972).

Silt and Clay. Particles between 4.0 and 8.0 Φ (0.0625 and 0.0039 mm) are silt, and particles smaller than 8.0 Φ are clay. Size-frequency distribution data are not easily acquired for the clay-size range, and thus the distributions shown in Figure 2-7 terminate at 8.0 Φ. Overlapping data do not permit a clear-cut statement, but it appears that for both silt and clay, oyster reefs contain less fines than adjacent non-reef areas.

Sand and Silt Grainsize Modes

Grainsize modes may provide fingerprints, identifying specific sources of particles, as suggested by Folk and Ward (1957). The purpose of the following discussion is to describe the sand and silt grainsize modes found in reef and non-reef sediments of St. Louis and Biloxi Bays. If significantly different grainsize modes are found for these two environments (and the sampling design is not faulty), then specific grainsize modes might provide clues to specific processes operating in reef and non-reef environments. The author judges these data to be preliminary only, and the above goal is not yet achieved.

St. Louis Bay samples reported here do not contain enough sand to enable accurate placement of sand modes, and therefore only two sand modes are shown in Figure 2. From other data, the commonest sand mode in St. Louis Bay is 2.25 Φ (Hoskin 1971b, Fig. 5, p. 182). Davis Bayou sand modes from the Spoil Bank (Figure 6) range between 2.25 to 2.75 Φ, averaging 2.50 Φ (0.177 mm); from Davis Bayou Reef (Figure 5), sand modes range between 2.25 to 2.38 Φ, averaging 2.31 Φ (0.205 mm). Each site was found to have 12 sand modes for 12 samples, and the sand modes are believed to be accurate to ± 0.125. It seems clear that the most frequently-occurring sand grains on the Spoil Bank are smaller than those in the Davis Bayou Reef, although the two sites are only 0.3 miles apart. Coarser sand in Davis Bayou Reef may indicate trapping of large grains, or conversely, removal of coarser grains from the non-reef spoil bank, assuming that both environments had the same sediment grainsize distribution at the outset.

Sand modes in the Biloxi Bay reef and from Marsh Point are considerably more variable, ranging between 1.88 to 3.50 Φ, and 1.38 to 3.65 Φ, respectively. There are

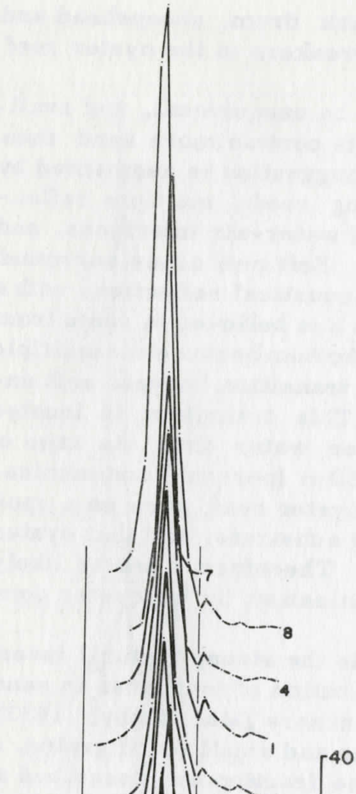

Figure 6. Size-frequency distribution for bottom sediment from the Davis Bayou Spoil Bank.

14 sand modes for the 12 samples from each site; average modal size is not meaningful due to the large variation. Marsh Point sand fractions are polymodal; the coarser mode is composed mostly of clear, angular quartz grains; the finer mode is composed of hematite-coated, angular grains, many of which appear to be a feldspar.

Silt grainsize modes were determined from pipet analyses. Reproducibility, as determined from 8 replicate analyses of mud from station 6 in the Biloxi Bay Reef, probably limits the usefulness of these data as modes apparently are accurate only to $\pm 1.0 \Phi$, although the analyses were made at one-half phi intervals. The commonest silt mode found in the 65 samples analyzed was 4.25Φ (0.053 mm), however, it is important to notice from the size-frequency distributions (Figures 2-7) that the 4.25Φ mode was not found in each and every sample. As there is a change of analytical technique at 4.0Φ (screens for sand, pipets for silt and clay), the 4.25Φ mode could be an artifact (Griffiths 1957). All samples of this report analyzed in the same way do not contain the 4.25Φ mode, and for this reason, it is believed to be real. Pipet analyses of 1536 samples from coastal Louisiana showed that 56 of 66 major water bodies contained a grainsize mode between 4.0 and 5.0Φ (Barrett 1971). It is tempting to suggest that the 4.25Φ grains are loess particles now being transported to coastal environments by rivers. Hydrometer analyses of 46 samples of "fresh" loess from inland Mississippi showed that the average median grain size was 5.62Φ (0.022 mm) and the average graphic mean size was 5.79Φ (0.018 mm, Snowden and Priddy 1968). Apparently, Mississippi-derived loess is finer grained than the coastal silt, but the different analytical methods, different measures of average grain size, and the possibility of selective size transport suggest that the loess merits further consideration as a source of the 4.25Φ coastal silt. Another possibility is that silt (other than loess) transported by the Mississippi River may be at least a part of the source as turbid surface water can be seen extending eastward from the river delta, at least at one instant in time, from earth satellite imagery (NASA photograph S-66-37810).

The next most-common silt mode, although much less abundant, is found at 6.75Φ (0.0094 mm) in sediments from the Biloxi Bay Reef, Marsh Point and Davis Bayou Spoil Bank. Generally, these silt size-fractions are polymodal; St. Louis Bay sediment has 31 silt modes in 12 samples, and this diversity is perplexing. Similarly, silt from the Biloxi Bay Reef contains 19 modes in 12 samples, Marsh Point silt has 25 modes in 12 samples, Davis Bayou Reef silt has 17 modes in 12 samples, and Davis Bayou Spoil Bank silt has 20 modes in 12 samples.

Oyster shells are known to accumulate sediment (Lund, 1957b, Figure 1, p. 321) and living oysters from the Marsh Point Reef and dead shells from the Davis Bayou Reef were collected and the accumulated sediment on the shells was scrubbed off in water with a nylon brush. The reason for adherence of the detrital sediment to the shells is not known to the author; one of the reviewers (Pilkey) suggested that an algal film might be involved. Size-frequency distributions for bottom sediment and for shell-accumulated sediment are compared in Figure 7. Sand modes for bottom sediment and shell-accumulated sediment are identical, and a good match was found for those samples containing silt modes from the Davis Bayou Reef. Sand modes from Marsh Point bottom sediment are clearly finer than sand modes from shell-accumulated sand; it is not known why this is so. Silt modes from Marsh Point bottom sediment and shell-accumulated sediment are similar, but not identical. This poor match is believed to be the result of experimental errors in the pipet analyses, and without the errors, the match should be closer than that seen in Figure 7.

Suspended Sediment

The average suspended sediment load for the Davis Bayou Reef as determined by differential weighing of membrane filters was 113 mg/l in late afternoon at slack water (low tide) following several hours of moderate wind, and the next morning at slack water (high tide) with several hours of calm wind, the average suspended sediment load had decreased to 81 mg/l. Tidal currents contribute to sustaining sediment in suspension, and bottom-feeding fish may contribute new sediment to the load. Measurement of tidal current velocities in early June (largest tidal variation, U. S. Dept. of Commerce 1970) with an Ott Arkansas V meter, showed that the near-bottom average velocity for the Marsh Point Reef was about 0. 5 ft/sec, and 0.2 ft/sec for the Davis Bayou Reef. Recall that a flow velocity of 0. 5 ft/sec is sufficient to entrain fine sand (Hjulstrom 1939; Inman 1963). Admittedly, many more measurements are needed, particularly during storms to evaluate the relative roles of tides and storm-caused waves and surge.

Grainsize Statistical Parameters

Many sediment studies have shown that size-frequency distributions tend to be characteristic, at least for some environments. Most sediments in this study contain large amounts of clay, which necessitated extrapolation of cumulative curves to 100 percent at 14.0 Φ in order to compute statistical parameters. This extrapolation may limit the usefulness of these data.

Mean Size. Sediment with a Gaussian distribution is unimodal, and the median, mean and mode coincide at the peak of the size-frequency curve. Sediments of this report, however, tend to be polymodal (Figures 2-7) and more meaning can be extracted from grainsize modes (above). The extremes of mean size reported here are - 1.25Φ (2. 38 mm) and 10. 08Φ (0. 00094 mm), with most sediments having a mean size in the silt size range between 4. 0 and 8. 0 Φ .

Standard Deviation. Uniformity of particle size-distribution is measured by the standard deviation; small numbers meaning great

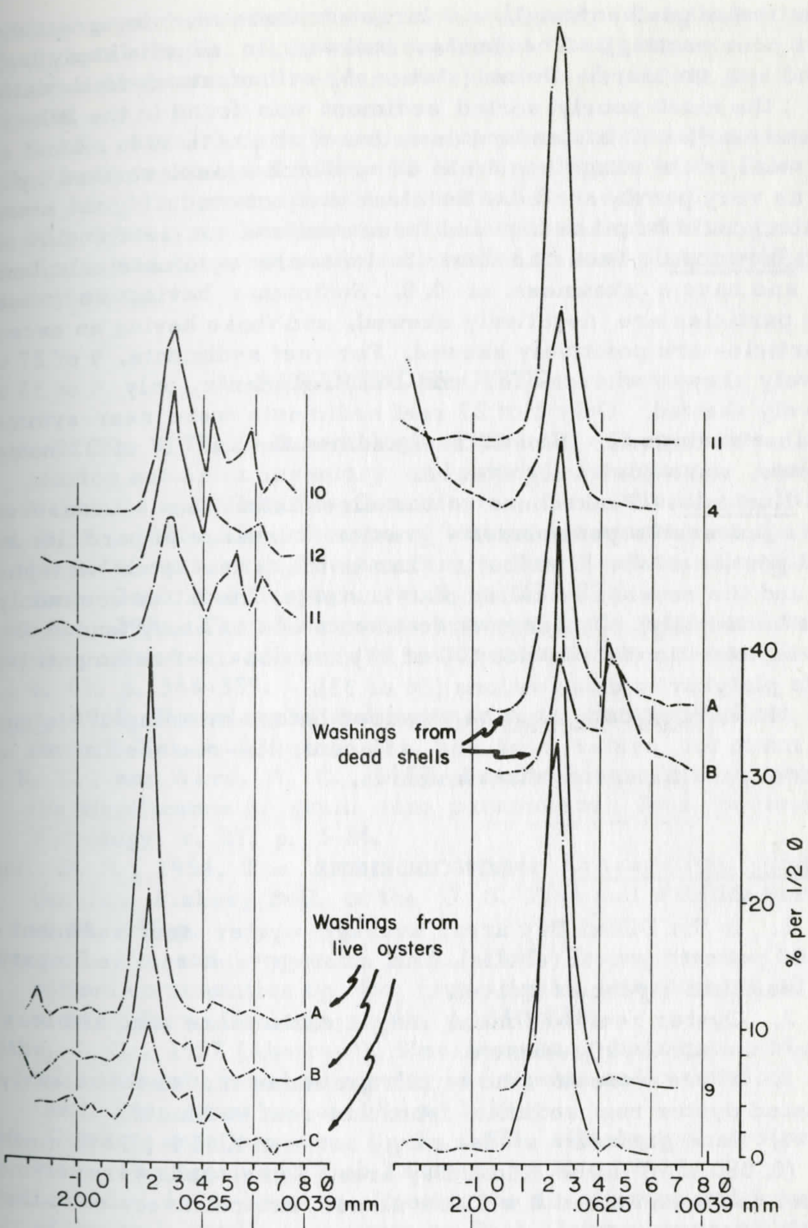

Figure 7. Size-frequency distributions for bottom sediment and sediment recovered from the shells of living oysters and from dead oyster shells.

uniformity (or good sorting), and large numbers meaning great diversity (or poor sorting). The best-sorted sample of this study is from the sand spit at Marsh Point (station 5) with a standard deviation of 0.38 Φ ; the most poorly-sorted sediment was found in the Biloxi Bay Reef (station 9) with a standard deviation of σ_I of 5.30 Φ . Most sediments were in the range $\sigma_I = 3$ to 4 Φ , which was described by Folk (1968) as very poorly sorted. No clear distinction, using the standard deviation, could be made between these reef and non-reef sediments.

Skewness. Gaussian distributions are symmetrical about the mean, and have a skewness of 0.0. Sediments having an excess of coarse particles are negatively skewed, and those having an excess of fine particles are positively skewed. For reef sediments, 9 of 27 were negatively skewed whereas for non-reef sediments, only 4 of 33 were negatively skewed. Only 2 of 27 reef sediments were near-symmetrical. Most sediments, 16 of 27 reef sediments, and 17 of 33 non-reef sediments, were positively skewed.

Kurtosis. Peakedness of the size distribution is measured by kurtosis (excessive peakedness - greater abundance of particles in the central portion of the distribution than in the tails - is called leptokurtosis, and the reverse is called platykurtosis, the latter commonly indicates bimodality). Oyster reef sediments of this study tended towards strong leptokurtic distribution (20 of 27) and non-reef sediments tended towards platykurtic distributions (24 of 33).

Much more data must be acquired before meaningful statements can be made for oyster reef and adjacent non-reef sediments using statistical parameters as discriminants.

CONCLUSIONS

1. In the Biloxi Bay area, average oyster reef sediment contained 10 percent gravel (shells), and average non-reef sediment contained less than 1 percent gravel.

2. Oyster reef sediment may contain more sand and less silt and clay than non-reef sediment.

3. There were no sand or silt grainsize modes that clearly differentiated oyster reef sediment from non-reef sediment.

4. Sand grainsize modes range between 1.88 Φ (0.272 mm) and 3.65 Φ (0.080 mm) in the Biloxi Bay area. Some sands were polymodal, and most sands contained a well-developed textural inversion in the 1.25 to 1.50 Φ (0.42 to 0.35 mm) size fraction.

5. Silt fractions tended to be polymodal, with the commonest two silt modes at 4.25 Φ (0.053 mm) and 6.75 Φ (0.0094 mm).

6. A fair match was found for size modes from bottom sediment and sediment accumulated on oyster shells.

7. Measured tidal current velocities were found to be sufficient to erode and transport bottom sediment of some reefs and spoil banks.

8. Suspended sediment was not uniformly distributed around reefs and spoil banks. Suspended sediment load increased during periods of wind-generated waves, and decreased during periods of calm winds.

9. No characteristic mean size or standard deviation was found for either reef or non-reef sediment. Most sediments in the Biloxi Bay area were found to be very poorly sorted and fine-skewed.

10. Oyster reef sediments tended to have leptokurtic grainsize distributions, and non-reef sediments tended to have platykurtic grain-size distributions.

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JET-RIG DRILLING TECHNIQUE FOR UNCONSOLIDATED SEDIMENTS

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ABSTRACT

An existing method of drilling water wells in unconsolidated sediments, by pumping water down a string of pipe, has wide geologic and engineering applications and is rapid, simple, and economic. Subsurface lithology, compactness, and stratigraphic contacts can be determined by feel transmitted through the hand-turned drill string, and then checked against returning sediments and water color. Pebble-sized chunks of clay are usable for microfossil studies, and macrofossils from horizons separated by 20 or more feet of clay can be used qualitatively for interpreting age or environment of deposition.

INTRODUCTION

Geologic field work in the Atlantic Coastal Plain is hampered by the low relief, few outcrops, and heavy vegetative cover that characterize the region. Road cuts and natural outcrops are chiefly along stream valleys. Artificial pits in interfluve areas are shallow, due to high water tables, and tend to be concentrated along depositional strike, especially along former shorelines. Such conditions make difficult the recognition and tracing of stratigraphic units and the determination of facies changes within the units.

Considerable recent interest in detailed studies of Quaternary and late Tertiary strata of the Atlantic Coastal Plain has necessitated the development of new techniques of coring and the evaluation of existing methods for obtaining subsurface information. Although coring techniques are invaluable for subsurface type sections and desirable for details where feasible, they are time-consuming and generally costly (Sanders and Imbrie, 1963, Shier and Oaks, 1966). Faster and less costly, but also less precise, methods of retrieving subsurface information are available for covering large areas in good detail. Such methods can aid considerably in making correct stratigraphic interpretations within given budget or time limitations.

Two rapid, simple, and relatively economic drilling methods for unconsolidated sediments already are in wide use by water-well drillers in the coastal plain: (1) the power auger, and (2) the jet-pump drilling rig (jet-rig). Smith (1961) has described and evaluated the use of the power auger as a geologic tool in the coastal plain. The purpose of the present paper is to provide a companion description and evaluation of the jet-rig for obtaining subsurface data rapidly, effectively, and efficiently.

Acknowledgments

Use of the jet-rig in stratigraphic studies was supported by the Virginia Division of Mineral Resources, James L. Calver, State Geologist. Curtis E. Widgeon and Louis Dickison, Londonbridge Well Drillers, gave us much valuable advice on many of the drilling techniques reviewed here. Additionally, C. E. Widgeon kindly donated the use of his small portable jet-pump and other equipment essential for us to make our own borings.

EQUIPMENT AND PROCEDURE

Jet-rig equipment can be minimal in both cost and amount, particularly in comparison with the power auger. However, a large and permanent jet-rig outfit can be nearly as expensive as a modest power-auger outfit. The jet-rig method requires: (1) adequate water supply; (2) centrifugal (jet) pump; (3) drilling pipe and cutting head; (4) three reinforced hoses (supply, intake, discharge); (5) pipe union, appropriate fittings, and hose clamps; (6) pipe-vise with attached handle; (7) pipe wrenches and shovel; and (8) miscellaneous additional equipment.

The basic unit consists of a gasoline-powered, one-cylinder, four-cycle motor that drives an attached centrifugal (jet) pump, which forces water under pressure through a hose and pipe union and down the inside of a drill string of pipe. For depths up to 500 feet, galvanized pipe is durable, light, and economic. A custom-made cutting head at the bottom of the drill string splits the water into several streams, and the water then returns to the surface along the outside of the drill string. There the water is caught in a series of shallow pits (settling basins) and recycled by means of a screened hose connected to the intake valve of the pump. When considerable water is taken up by

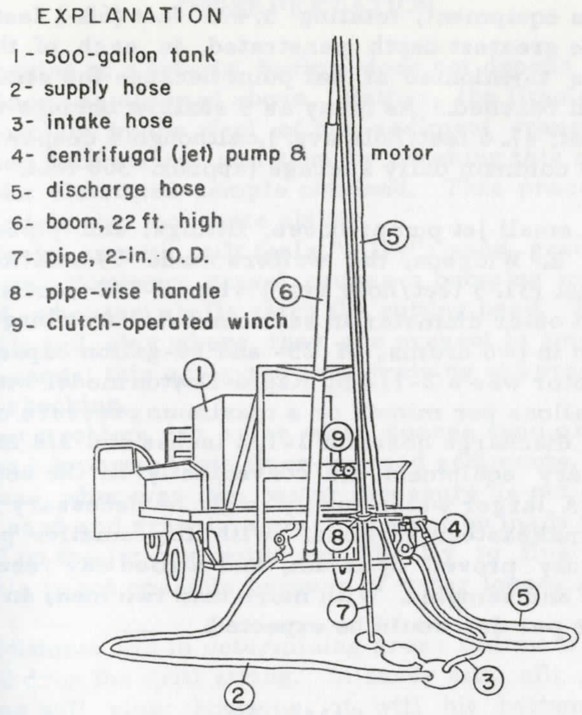

Figure 1. Sketch showing truck-mounted equipment used by C. E. Widgeon, Londonbridge Well Drillers.

permeable horizons, the water level of the shallow pits must be maintained by additions from the main water supply via the supply hose, so that the intake hose remains covered and the pump vacuum is not lost. During drilling the pipe string is twisted back and forth in the sediment and also is lifted and dropped by means of a pipe-vise handle attached to it above ground.

The writers became acquainted with the jet-rig method during a drilling program carried out under contract between C. E. Widgeon, Londonbridge Well Drillers, and the Commonwealth of Virginia, Division of Mineral Resources. The equipment used by Widgeon was truck-mounted, and consisted of a 500-gallon water supply; a boom 22 feet high; a clutch-operated rotating winch ("cat") run by the truck motor, used to pull up the drill string with 3/4-inch rope; and a separate jet pump motor (Figure 1). The motor was a 9-hp Marlow-Wisconsin model with a maximum volume of 60 gallons per minute or a maximum pressure of 55 psi with intake and discharge hoses of 2 inches and 1-1/4 inches respectively. Pipe sections were 20 feet long with 2-inch outer diameter, marked in intervals of 5 feet. A total of 51 borings were drilled with this equipment, totaling 3,475 feet (68.1 feet/hole avg.); 120 feet was the greatest depth penetrated, in each of three borings, and drilling was terminated at that point because the stratigraphic objective had been reached. As many as 9 shallow borings were made in one day (429 feet; 47.6 feet/hole avg.), although 4 deeper borings constituted a more common daily average (approx. 300 feet, or 75 feet/hole avg.).

Using a small jet pump, hoses, fittings, and pipe-vise handle belonging to C. E. Widgeon, the writers made 69 additional borings, totaling 2175 feet (31.5 feet/hole avg.) with 52-1/2 feet of galvanized pipe of 1/2-inch outer diameter in sections 3-1/2 feet long. Water supply was carried in two drums, of 25- and 50-gallon capacity, respectively. The motor was a 2-1/2 hp Rapid-Dayton model with a maximum volume of 50 gallons per minute or a maximum pressure of 35 to 40 psi with intake and discharge hoses of 1-1/2 inches and 3/4 inch respectively. All necessary equipment fit conveniently in the bed of a one-ton pickup truck. A larger water supply might be necessary in areas less swampy than southeastern Virginia. With the smaller pump three or four borings a day proved optimum, and a good day resulted in 125 to 160 feet logged and sampled. With more than two men, an even greater aggregate depth per day would be expected.

SAMPLES

The water pumped down the drill string provides a continuously rising water current that carries sediment along the outside of the drill string to the surface, where both the water and sediment flow along a shallow spillway into a sediment basin, then along a second spillway and into a second settling basin. Here the water is sucked up with a screened hose attached to the jet pump and recycled.

The sample, therefore, is separated into size grades both in the hole and above ground by elutriation in the flowing water. Sand collects in the first spillway and settling basin, silt chiefly moves on into the second spillway and settling basin, and clay collects either as rounded pebble-sized chunks in the first basin (rapid drilling), or as small blebs in the second basin, or else goes into suspension and is recycled along with the water (slow drilling).

A sandy silty clay will produce first silt and small clay blebs, later sand and larger clay chips, and finally large rounded pieces of clay. Sample collection, therefore, becomes an art of knowing both where and when to collect, and of necessity is heavily dependent on the driller's assessment of the lithology for proportions of each size grade. For these reasons samples must be collected with care, both to represent a given interval, and to characterize the actual sediment type, as described next.

INTERPRETATION

The logging of a jet-rig boring does not depend entirely on the samples obtained, as outlined above. Rather, the lithology more commonly is determined by the feel of the sediment transmitted through the hand-turned drill string, and then by checking this assessed lithology against the elutriated sample obtained. This procedure required training, practice, and moderate ability.

Clay feels smooth, silt feels "silky", sand grates, and gravel and shells rasp. However, gravel causes a bumping movement as the pipe is turned, whereas shells catch the cutting head. It is difficult to recognize silt and clay where they are present in small to moderate amounts with sands; this again requires training and practice, plus constant sample checking.

Another problem can arise when coarse sand or gravel follows the cutting head downward into finer-grained sediments. Because this situation occurs whenever the water pressure is not great enough to pump out the sand and gravel, a practice must be made when drilling in sand to speed up the jet-rig motor periodically to flush out the hole. Sometimes this is not possible because of water losses into sandy aquifers.

An additional aid in determining gross sediment composition is to pick up and drop the drill string. In sandy silt, silt, clay, or peat, the drill string will sink; however, it will hit bottom hard in sand, gravel, or silty sand, even where the sand is loose and drills rapidly.

Sediment color commonly can be determined as readily from the water color as from the sediment itself. Water reaches the surface in less time than the sediment that imparts a new color; thus, a contact is first felt, then noted in the change in water color, and then observed in the change in both sediment color and grain size.

An advantage of the jet-rig method over the power auger is in the recognition of very thin interbeds of varying lithologies, determined by feel. Unless the drill string is pulled for each new flight of the power auger, samples from both the power auger and the jet-rig are so mixed as to prevent detection of such interbeds if they are less than a few feet thick.

LOGS

Detailed lithologic logs of jet-rig borings are made from the driller's description of sediment based on its feel, and modified by the samples actually obtained. Also recorded are the date, location, approximate surface altitude, total depth, depths to contacts, thicknesses of units, and the depth when each sample was taken. A sample log is shown in Table 1. Each day's logs are then checked the same evening for inconsistencies or omissions in sample numbers, descriptions, or depths.

Table 1. Sample log.

Date: June 27, 1963
Boring No.: W-1044
Alt.: Approx. +15 ft.
Locn.: Deep Creek 7 1/2-min. quad., Keith propt'y, south side West Landing Road (Rte. 625), 0.7 miles
U.S. 17. Latitude 36° 38'55" N, Longitude 76° 21' 29" W.

Unit	Sample No.	Depth (Feet)	Thick. (Feet)	Major Materials	Minor Materials	Color	Soft Loose	Compactness (clay) (sand)	Firm Compact
		0	0	Ground Surface					
Dismal Swamp Peat				Clay, silty, highly organic, dk. brn., soft.					
		1	1						
Sand Bridge Fm., Upper Member				Silt, clayey, tr. sand, lt. gray, mott. yell., firm.					
		4	3						
Sand Bridge Fm.,	1	6	2	Sand, fine, lt. brn., loose.					
		8	2						
Lower Member				Sand, fine, gray, loose.					
	2	10	2						
Londonbridge Fm.				Clay, gray, firm					
	3	14	4						
Norfolk Fm., Upper Member				Sand, fine, silty, gray, loose, many shells, chiefly Ensis directus.					
	4	21	7						
				Sand, fine to med., gray, loose, many shells.					
	5	26	5						
Norfolk Fm., Lower Mbr.				Sand, med. to coarse, gray, loose, some shells.					
	6	31	5						
Yorktown Fm.	7	35	4	Clay, green-gray, very firm: stiff; a few shells, including Divaricella sp. and Ensis directus.					
		37	2						
				Sand, fine to med., gray, compact.					
	8	42	5						

APPLICATIONS

The first macrofossils encountered in boring (or fossils from horizons separated by 20 feet or more of barren clay, which coats sides of the hole) can be used qualitatively for environmental interpretations and for age determinations, particularly when recovered shells include small, fragile, articulated specimens showing little evidence of reworking. Large shells commonly are broken up in the drilling process, a factor that must be considered in any interpretation. Additionally, rapid drilling in clay provides large, pebble-sized chunks suitable for microfossil studies.

Foundation characteristics can be compared with degree of compactness for each stratigraphic unit by drilling a core test and an adjacent jet-rig boring. Contacts between stratigraphic units then can be picked in surrounding areas on the basis of degree of compaction, determined by the jet-rig method. In some cases this approach is applicable through rather wide regions (Harrison and others, 1965; Oaks, 1965). Conversely, one or two core tests can be paired with a large number of jet-rig borings in a limited area to provide close subsurface detail required for foundations, and for economic clay, sand, and gravel resources, at a lesser cost, or with a better coverage, than the exclusive use of core tests affords. The quality of water in a given aquifer can be tested readily by reversing the intake and discharge jet-pump hoses. Obviously, the jet-rig has many applications for the engineer and the geologist when used by trained personnel.

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GEOHYDROLOGY OF COLLIER COUNTY, FLORIDA *

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ABSTRACT

Southwestern Collier County, Florida is presently undergoing growth in population with consequent increases in their water demands. Although rainfall is abundant, losses due to evapotranspiration and oceanic discharge are equally large. This paper discusses the subsurface geology of the two main aquifers underlying the area. Well logs, and drillers logs are the main tool for understanding the subsurface geology of this low, poorly-drained, flat plain. The shallowest aquifer is composed entirely of permeable limestones in the Tamiami Formation. The deeper Floridan aquifer is artesian and contains two basic parts, an upper one yielding fresh water, (Hawthorn Formation) and a lower part yielding salt water (Tampa Formation). The two layers of the Floridan aquifer are separated by an aquiclude. Directions of flow, water quality and future potential of all these hydrologic units are also examined.

INTRODUCTION

Southwestern Collier County, Florida has recently begun to experience substantial growth in population. This paper reports the results of an investigation into the two most important aquifers in the area: (a) a shallow aquifer primarily composed of permeable late Miocene limestones and (b) the Floridan aquifer also containing permeable limestone strata of Miocene age.

The area under investigation (Figure 1) is bounded to the north by Lake Trafford and the city of Immokolee, to the east by the Turner River Canal, to the south by Everglades City and the Tamiami Canal, and to the west by the Florida coastline.

*Work conducted at Wright State University, Dayton, Ohio.

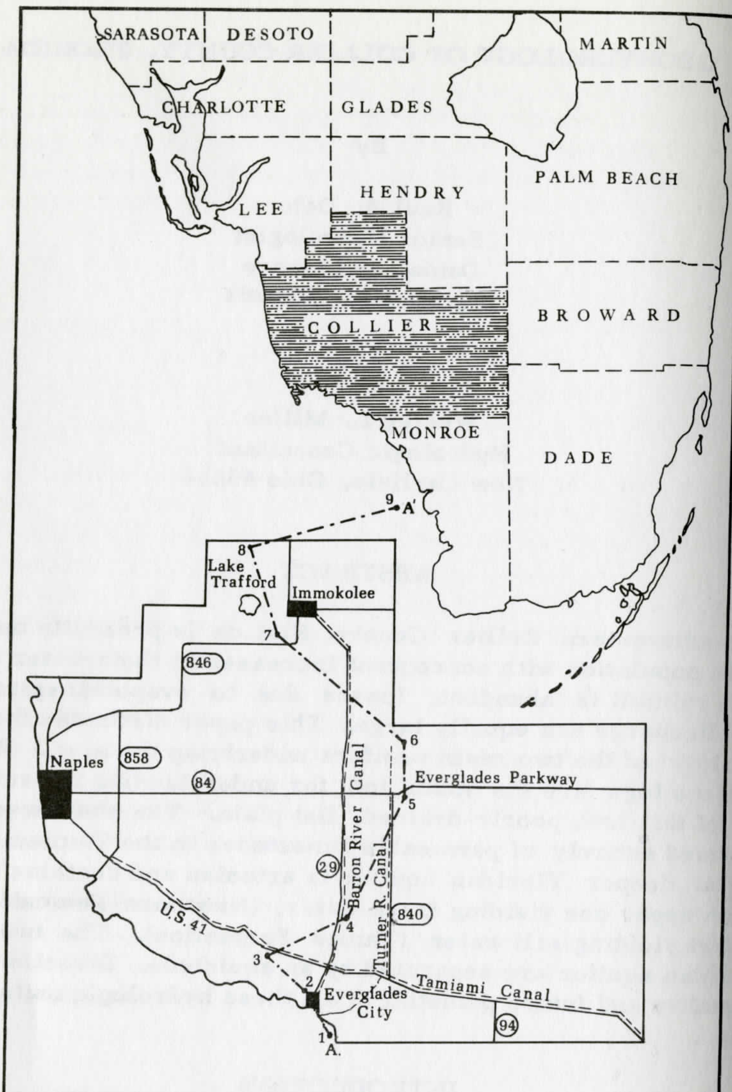

Figure 1. Area under investigation. Line A-A' refers to the wells used in the stratigraphic cross section depicted in Figure 3.

The land is a low (maximum elevation about 8 feet above mean sea level), poorly drained, flat plain. The plant life consists of a salt-water marsh and a fresh-water marsh with scattered pine - palm - palmetto forests and cypress forests. Present artificial drainage is limited to three major canals (Figure 1). The natural drainage consists of several poorly defined streams. These streams drain large areas of swamp over which large quantities of water flow imperceptibly during the wet season.

Several reports have treated the ground water resources of portions of the area under investigation (Klein, 1954, McCoy, 1962, and Klein, et. al., 1970). This paper agrees with the findings of previous authors and extends their work to achieve a comprehensive picture of the subsurface hydrogeology of Collier County.

Data gathered for this investigation in addition to field work include electric well logs, drillers logs, aerial photographs, runoff data, geologic base data, climatic data and water quality information.

SURFACE WATERS

While the yearly rainfall is large throughout Collier County, the evapotranspiration rate is high. The difference between precipitation and potential evapotranspiration for the area is 0 to 3 inches (Vishner and Hughes, 1969). This limits the amount of water available for infiltration and runoff. During the dry season (November-April) evapotranspiration may exceed precipitation (Leach et. al., 1972).

A water management program is needed to reduce evapotranspiration rates and rapid discharge into the sea. Evapotranspiration is greatest in the warmer summer months but constitutes a more serious water loss during the winter season when precipitation is low. During the rainy season, water management is needed to reduce the discharge of water into the sea and to prevent flooding. Water controls should provide gathering points from which excess water may be drawn for useful purposes, thus reducing runoff losses.

Surface sheet flow covers up to 90 percent of the area in the wet season and as little as 10 percent in the dry season. The direction of flow (Figure 2) is generally southward and westward. During the dry season, runoff is limited to the several strands in the area.

GEOLOGY

In the area investigated the only materials which yield water of sufficient quantity and quality for domestic, municipal, or agricultural uses are of Miocene age. The older Oligocene and Eocene materials yield larger quantities of water from flowing wells, but the water is too highly mineralized for most purposes. Water levels in artesian wells penetrating these older formations vary from 25 feet above mean sea level along the coast to 55 feet in northern Collier County (Healy, 1961).

The Miocene Series in Collier County consists of three formations in ascending order: the Tampa, Hawthorn, and Tamiami. The predominant materials in these formations are limestone, sand, and clay mixed with varying amounts of shell and marl. Limestones in the

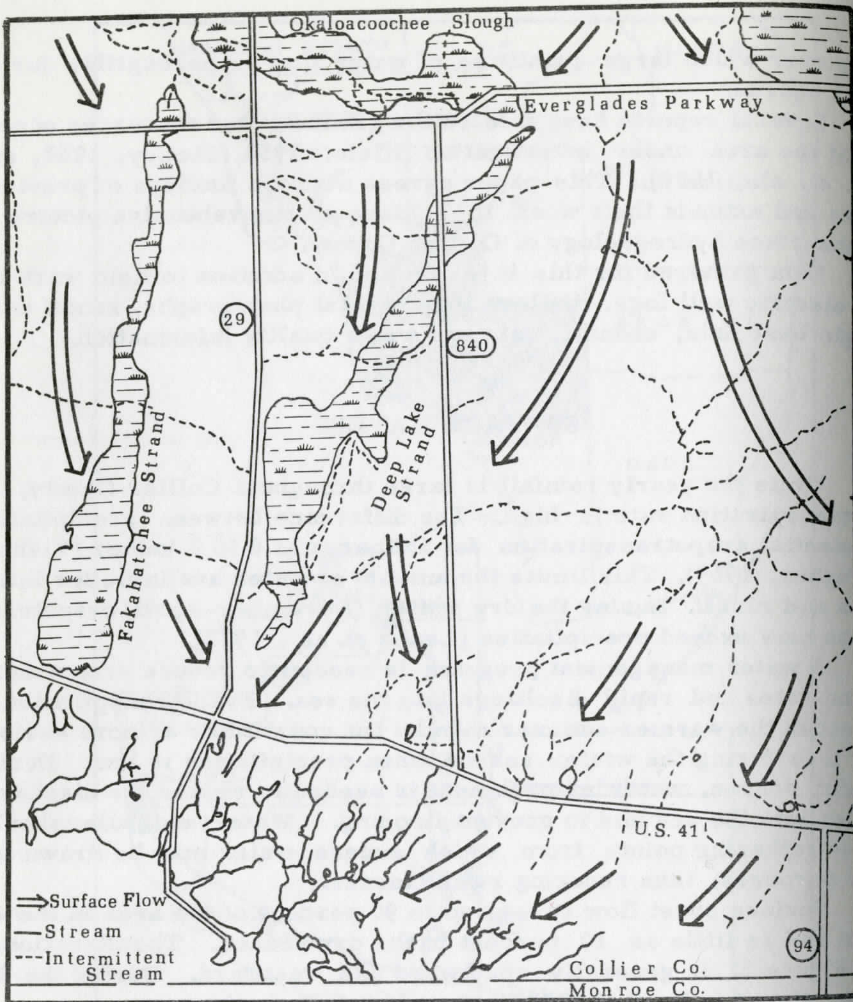

Figure 2. Direction of surface flow.

lower part of the Hawthorn are considered the upper part of the Floridan Aquifer (McCoy, 1962). Similar water levels in wells penetrating different portions of the Floridan Aquifer led Parker, et. al., (1955) to believe that the Hawthorn and Tampa Formations are hydrologically interconnected. Electric and gamma logs examined by the authors indicate a tight clay-rich limestone aquiclude which separates the formations and allows little interconnection of water. Abandoned and uncased wells probably provide the maximum connection between portions of the aquifer.

The water-bearing formations are discussed below in further detail. Line A-A' (Figure 1) indicates the position of wells 1 through 9

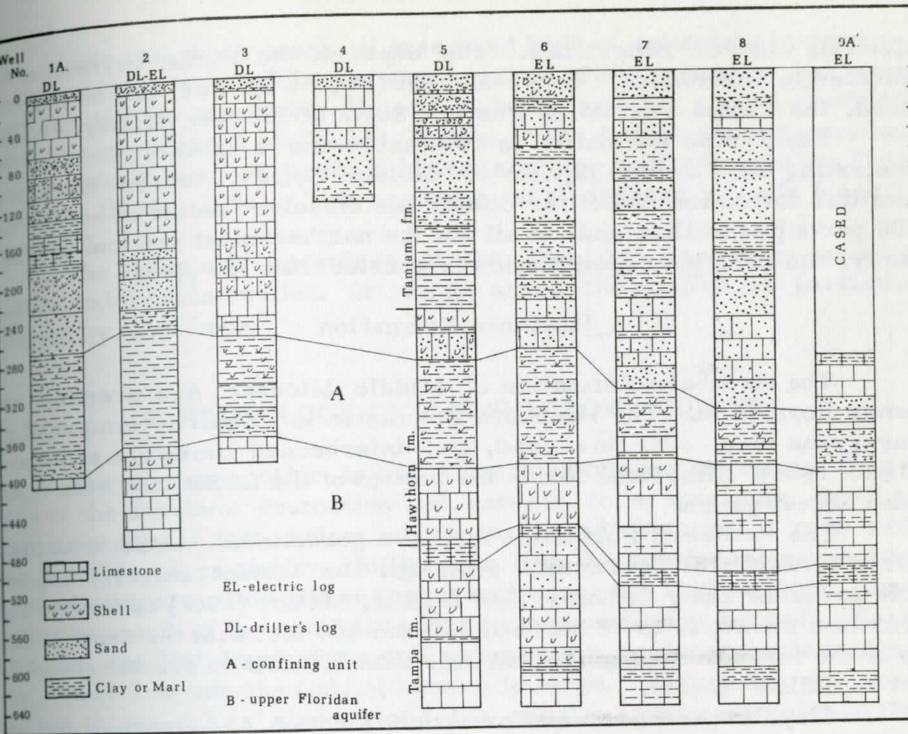

Figure 3. Cross section constructed from electric and driller's logs along line A-A' (Figure 1).

for which electric and/or driller's logs are available. Figure 3 is the lithologic cross-section along Line A-A' as interpreted from available logs.

Tampa Formation

The Tampa Formation overlies the Suwanee Limestone of Oligocene Age and is gradational with the overlying Hawthorn Formation. The major components of the Tampa Formation in Collier County are sandy limestone and calcareous sandstone. The predominantly quartz sand occurs either as thin lenses or pockets disseminated in the limestone matrix (Klein, 1954).

The boundary between the Tampa Formation and the overlying Hawthorn Formation is distinctly evident on electric and gamma-ray logs. The formations are separated by a unit which displays a marked decrease in spontaneous potential and resistivity and an increase in gamma-ray response The unit appears to be 10 to 20 feet thick and is bounded on either side by increased resistivity and spontaneous potential. Logs examined indicate a limestone and clay unit separating relatively cleaner limestones. The depth to the Tampa Formation is indicated in the lithologic cross-section (Figure 3). In a well on Marco Island, the Tampa Formation lies at a depth of 350 feet (McCoy, 1962).

The Tampa Formation is the main source of water from wells penetrating the Floridan Aquifer in Collier County. Water extracted from this formation in Collier County has dissolved solids in excess of 1000 parts per million and, in all but the northernmost section of the county, the chloride concentration is greater than 100 ppm.

Hawthorn Formation

The Hawthorn Formation of Middle Miocene Age overlies the Tampa Formation. The Hawthorn Formation is primarily composed of gray-green clay, silt, fine sand, and interbedded limestone and marl (Klein, 1954). Limestone forms the bottom of the formation in the area under investigation.

The Hawthorn Formation forms a gradational contact with the overlying Tamiami Formation. Although the contact is nearly impossible to locate using lithology and fossils, McCoy (1962) estimated the formation thickness to be between 250 and 300 feet with the depth to the top of the formation ranging from less than 100 feet to greater than 200 feet in Collier County.

Clays in the Hawthorn Formation (Section A, Figure 3) act as the confining unit of the Floridan Aquifer. Well logs from well 1, Chokoloskee Island, on Line A-A' indicate a clay layer 130 feet thick beginning at a depth of approximately 270 feet. Driller's logs from well 2, Everglades City, describe the clay as tough, green, and impermeable. Proceeding northward along Line A-A', the clay layer thins, becoming mixed with increasing amounts of sand and shell. In wells 7, 8, and 9 it is only about 60 feet thick.

The most hydrologically interesting portion of the Hawthorn Formation is the series of limestone (Section B, Figure 3) lying between the clay layer and the top of the Tampa Formation. These limestones are the uppermost portion of the Floridan Aquifer and are tapped by the municipal wells of Everglades City. Water from this unit is characterized by significantly lower chloride concentrations than deeper portions of the Floridan Aquifer. The water-bearing zones consist of permeable limestone layers 1 to 7 feet thick separated by dense, less permeable limestones.

Tamiami Formation

All deposits of Late Miocene Age in southern Florida have been assigned to the Tamiami Formation by Parker et. al., (1951). Klein (1954) noted that the uppermost portion of the Hawthorn Formation is part of the Tamiami Formation. The formation is composed primarily of light tan and gray fossiliferous sandy limestone and interbedded gray-green sandy and shelly marl. Lenses and beds of relatively impermeable greenish-gray marl in the upper portion of the formation act as a confining unit to permeable limestone beds, forming a semi-confined aquifer in some areas of Collier County. In the Naples area the permeable limestone lies at a depth of 50 feet and dips gently toward the Gulf of Mexico (Klein, 1954). The confining marl appears in wells 6 and 7 (Figure 3).

The sands and limestones in the Tamiami Formation act as a shallow water table aquifer. In some areas the aquifer is partially confined by marl beds.

GEOHYDROLOGY OF THE SHALLOW AQUIFER

The shallow aquifer in the area is composed entirely of limestone of the Tamiami Formation and extends to a maximum depth of approximately 160 feet, below which increased amounts of sand and clay limit the permeability. Infiltration into the aquifer is impeded by relatively impermeable silt and marl units near the land surface. Consequently, much of the rainfall is lost by evaporation and runoff. Near the coast, the high level of the salt water boundary also retards infiltration. Sheet flow into the Gulf of Mexico is large. During the wet season, recharge takes place along the canals and in sinkholes in the southern portion of Collier County.

Using available water analyses previously reported by McCoy (1962) we examined the characteristics of the water in the shallow aquifer.

Contour maps of the concentrations of inorganic constituents in the shallow aquifer were prepared by the authors. Figure 4 illustrates contours of equal concentrations, in parts per million, of calcium, magnesium, sodium, and chloride. The direction of groundwater flow in the shallow aquifer is from north to south, down the topographic gradient. The concentrations of calcium, magnesium, sodium, and chloride decrease in the direction of flow. This, in addition to indicating the absence of salt water intrusion in central Collier County, suggests that the aquifer is being freshened.

One explanation of this could be leakage from the upper portion of the Floridan Aquifer which is under an artesian pressure of 50 to 55 feet. Any water leaking upward from the Floridan Aquifer into the shallow aquifer would be diluted by rainwater infiltration and the concentration of inorganic constituents would decrease.

While it is probable that minor leakage through the confining units of the Floridan Aquifer does occur, there is no indication of major leakage in the area contoured. Piezometric surface studies presented by Healy (1961) and McCoy (1962) indicate no rapid decreases as would be expected if faults or other major breaks in the confining unit existed. In addition to this, water leaking upward from the Floridan Aquifer

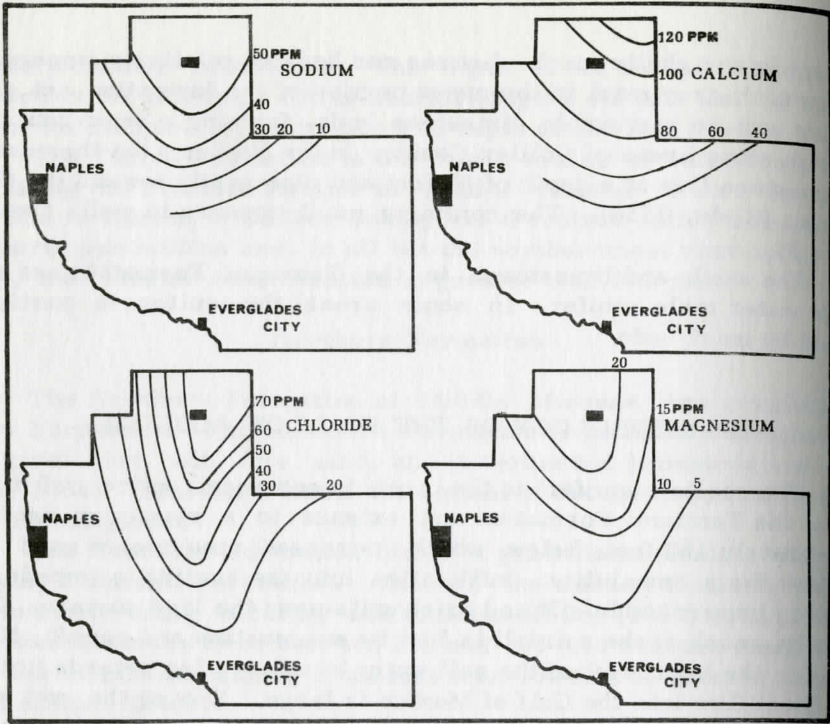

Figure 4. Contours depicting the concentrations of sodium, calcium, chloride, and magnesium in the shallow aquifer.

would contain a much higher concentration of chloride than that observed in the shallow aquifer. Chloride concentrations in the Floridan Aquifer are approximately five times higher than those in the shallow aquifer. In addition to this, McCoy (1962) noted that test drilling showed little difference in head exists between the upper and lower portions of the shallow aquifer. The hydrostatic head of the lower portion of the shallow aquifer was tested to 230 feet below land surface. This testing indicates that minor leakage from the Floridan Aquifer will not seriously contaminate the shallow aquifer.

The decrease in the concentrations of inorganic constituents is better explained by increased flushing of the shallow aquifer as a result of canals in the area. Poor flushing of the groundwater accounts for the relatively high mineralization of the groundwater in the interior of Collier County (McCoy, 1962). Near surface beds of impermeable limestone and marl retard infiltration of rainfall. Also, there is little relief to the topography, and the water-table gradient is nearly flat. Numerous canals have been constructed in north central Collier County as sources of road fill. These canals increase the water-table gradient and improve the flushing of the shallow aquifer. The validity of this process was demonstrated in wells northeast of Naples (McCoy, 1962).

The rapid decrease in calcium is partially due to precipitation of calcium carbonate. The equilibrium pH with respect to $CaCO_3$ in the shallow aquifer is consistently less than the measured pH indicating carbonate supersaturation. Even minor changes in temperature or pressure will cause precipitation of calcium carbonate.

The decrease of chloride concentration is impeded by chloride contamination in rain water blown inland from the ocean. Chloride concentrations of the order of 2 to 3 parts per million are common in rain water with higher concentrations during hurricanes. This, coupled with high evaporation rates which concentrate the chloride, slows removal of chloride from the aquifer.

FLORIDAN AQUIFER

The Floridan Aquifer is a confined aquifer which underlies most of Florida. The Floridan Aquifer includes all parts of the thick permeable limestone of Middle and Late Eocene Age and Oligocene Age, the Tampa Formation, and permeable limestones of the lower Hawthorn Formation (Parker, et. al., 1955). The Floridan Aquifer is confined by impermeable clays and relatively impermeable limestone in the Hawthorn Formation. Clay, silt, and marl units in the lower Tamiami Formation increase the efficiency of the confining layer.

In the area under investigation, the main confining unit of the Floridan Aquifer is a thick clay layer in the Hawthorn Formation. The clay, described by drillers as tough, green, and impermeable, is 100 to 130 feet thick in wells 1, 2, and 3 (Figure 3) and is encountered at a depth of approximately 260 feet below the land surface. Semipermeable limestone and marl units in the overlying Tamiami Formation also act as confining layers.

To the north of the area under investigation, along Line A-A' (Figure 1), the clay unit in the Hawthorn Formation thins to approximately 60 feet thick in well 7 and 45 feet thick in well 8. The thinning of the clay confining unit is offset by an increase in the number of clay and marl units in the overlying Tamiami Formation, which act as confining units.

Limestones of the Hawthorn Formation lie directly below the impermeable clay unit. This is the uppermost portion of the Floridan Aquifer and is encountered at a depth of 360 to 400 feet below the land surface. The total thickness of the Floridan Aquifer may exceed 2000 feet in some areas of Collier County.

The recharge area for the Floridan Aquifer is over 100 miles north of Collier County, in Polk County and vicinity where leaky confining units overlie the aquifer (McCoy, 1962). The relatively lower chloride concentrations in the Hawthorn Formation indicate that lower concentrations of connate chlorides were trapped in the upper portion of the aquifer or that this portion of the aquifer was flushed better. Local recharge of the Floridan Aquifer in Collier County is unlikely due to the low hydraulic conductivity of the confining units and the high artesian pressure of the aquifer.

In Collier County water is discharged from the Floridan Aquifer by a number of flowing wells. McCoy (1962) estimated about 50 wells in use and an undetermined number of abandoned wells which have either not been capped or have leaky casings. It is estimated by the authors that the present number of wells now in use has at least doubled since 1962. The municipal and industrial wells in Everglades City constitute the major discharge from the Floridan Aquifer in southern Collier County.

The high artesian pressure near the coast coupled with the steep gradient of the piezometric surface south of U. S. Route 41 indicate large discharge from the Floridan Aquifer in offshore areas in the Gulf of Mexico.

CONCLUSIONS

Collier County, Florida, is presently growing in population, industry, and water needs. Rainfall is the greatest potential source of fresh water in the area with an annual average of 53.8 inches. At the present time, with minimal water control and large evapotranspiration losses, the estimated discharge increase between the Everglades Parkway and the Tamiami Canal (Figure 1) is 301 cubic feet per second or 38.5×10^7 gallons per day during September when rainfall is greatest. While some of this increase is due to natural discharge from the shallow aquifer, most is from rainfall. Without sufficient controls, most of this water flows into the Gulf of Mexico and the Everglades.

The shallow aquifer is the principal source of fresh water in Collier County. It is composed entirely of permeable limestones in the Tamiami Formation.

The Floridan Aquifer is a confined aquifer which underlies all of Collier County. Wells penetrating the aquifer flow under artesian pressure. In the area under investigation, the Floridan Aquifer flows primarily through permeable limestones in the Hawthorn and Tampa Formation. Only those wells which extract water from only the Hawthorn Formation in the Everglades City area yield water of drinkable quality. Wells penetrating the Tampa Formation yield highly mineralized water throughout Collier County.

The uppermost portion of the Floridan Aquifer, at a depth of 360 to 400 feet, is in the Hawthorn Formation and is separated from the rest of the aquifer by an aquiclude. The uppermost portion of the aquifer is 60 to 100 feet thick and contains fresh water. Using electric logs, the fresh water in the Hawthorn Formation may be traceable northward from the Everglades City area. Wells penetrating deeper portions of the Floridan Aquifer allow leakage of highly mineralized water to contaminate the upper portion of the aquifer if the wells are uncased, or have leaky casings. This is of particular concern when heavy pumping reduces the hydrostatic head in the upper portion of the aquifer.

The uppermost portion of the Floridan Aquifer could provide a large supply of fresh water for the area under investigation. A system of artificial recharge wells could be designed to increase the quantity and quality of the water available while increasing the hydrostatic pressure and preventing further salt water contamination of the aquifer.

All uncased and abandoned wells penetrating both the Hawthorn and Tampa Formation should be located and either tightly cased or filled to prevent the flow of water between sections of the Floridan Aquifer. Even with artificial recharge, the hydrostatic pressure in the uppermost portion of the aquifer may be reduced by heavy pumping during periods of peak demand. This may allow upward leakage from the Tampa Formation around poorly constructed or maintained wells.

Before the water resources of the area have been fully developed, strict regulations regarding well construction, pumping rates, and water uses must be observed. At best, a delicate balance will be achieved and minor excesses in water use could easily cause renewed salt water intrusion, extensively damaging the hydrologic resources. Any inconvenience to residents of the area by such restrictions will be more than offset by the guarantee of high quality drinking water.

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